

DEVELOPMENTS IN AGRICULTURAL
AND MANAGED-FOREST ECOLOGY 26

agriculture in dry lands

principles and practice

I. ARNON

A stylized graphic of agricultural plants, including wheat and corn, rendered in blue and green, set against a dark green background. The plants are arranged in a row, with some taller and some shorter, creating a sense of depth and growth. The design is minimalist and modern, using solid colors and simple shapes to represent the crops.

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Foreword

The dry lands with which this work is concerned, are the areas of meagre or undependable rainfall, in which the average precipitation is deficient in relation to water requirements. These include the arid zones, in which arable crop production is not possible without irrigation, and also their semi-arid fringes, in which rainfall, though precarious, is sufficient for certain types of crops, requiring special management techniques.

It is an interesting fact of history that in most of the dry lands in the Near East, India, North Africa, and Central Africa, very advanced agricultural civilizations developed, flourished, and eventually disappeared.

Whatever the reasons that prompted early man to choose the arid and semi-arid lands, in preference to the more favourable conditions for agriculture of the temperate regions with more reliable rainfall, it is clear that he chose an environment in which the balance between his own activities and the environment is extremely precarious.

The central problem of sustained land use in the dry regions has always been to find and maintain a balance between man's requirements and the productive capability of the land. This has rarely been achieved in the long run.

Throughout history, man has, by over-use, consistently reduced the productive capacity of dry lands. Originally, a large proportion of the more or less scanty vegetative cover consisted of palatable and nutritious grasses and shrubs. Overgrazing caused an overall reduction of the plant cover, and the large-scale replacement of useful plants by unpalatable species. The reduced cover intensified erosion by wind and rain, starting a process which is frequently irreversible. Gullies cut through alluvial valleys, water run-off increased, and water-storage reservoirs filled with silt.

Where the original plant cover of areas on the fringes of the arid regions was ploughed up for crop production, the consequences were still more disastrous. The classic, though by no means isolated, example is that of the 'dust bowl' of the Great Plains of North America.

In most dry land areas in which irrigation agriculture was developed, the consequences of cultivation were in the long run no less catastrophic; salinization and

water logging have reduced once-fertile regions to barren wastes. Economic deterioration was accompanied by political instability and the inability to withstand invasions of nomadic tribes. Wide areas were gradually abandoned, and the erstwhile cradles of civilisation became man-made deserts.

All this might be only of historical interest; unfortunately the degradation of the dry lands of the World is not only continuing, but is actually accelerating. With the explosive increase in world population, there is increasing pressure on the arid lands, which, with their semi-arid fringes, constitute fully one-third of the land area of the globe. This increased pressure applies mainly to the areas with primitive agriculture and low standards of living; but even the technologically advanced regions with a high standard of living are facing serious problems of deterioration of their natural resources.

The dry lands of a great number of countries are now usually vast empty areas. A large proportion is desert, and its contribution to food production is minimal. Other vast areas, on the fringes of the deserts, in Africa and Asia, with a rainfall that is just sufficient or even adequate to grow a single adapted crop, are still cultivated by primitive methods that have not changed since biblical days – with resultant low yields. In other vast areas, with similar climatic conditions – in the former USSR, North America and Australia – though cultivation is with the most modern equipment, the yields are often low compared with those that are common in regions of temperate climate. And yet, the combination of high insolation, favourable temperatures, and long growing periods, make possible levels of agricultural production that can exceed considerably those achieved in the temperate regions – if only an adequate supply of water can be provided.

There are however, areas, both rainfed and irrigated, that were formerly desert or seasonally dry, which produce a large variety of crops with record yields – an indication of the potential of the world's dry lands when water is no longer a limiting factor and modern technology is wisely and prudently applied. The development of other dry lands along the same lines could make substantial contributions to the economies of the countries involved and to increasing food supplies for the world as a whole.

In recent years, public awareness of the dangers inherent in the accelerating degradation of dry lands, pollution of the environment and the impending food shortage as population continues to increase explosively, has directed the attention of international and other agricultural bodies to the dire need for preserving and developing more effectively the agricultural potential of the dry lands.

World interest in this subject is evidenced by the numerous symposia and workshops and the promotion of research that has a bearing on the problems of dry lands; as a result of such research, numerous papers have been published and a huge store of important data on the dry lands and the problems of their development has become available. What appears to be lacking is the condensation of that which appears most relevant in this mass of information to the problems of agricultural production in the arid regions and their semi-arid fringes.

Twenty years ago, I attempted such a condensation in a work entitled *Crop Production in Dry Regions*, published by the since defunct Leonard Hill Books, and out of print for many years. It was felt that the current importance of the subject justified a new edition of this book. Originally, the intention was an updated version of the original. However, in the course of preparing the manuscript, it became clear that progress made in the course of the last two decades on all aspects of agricultural technology and development was so considerable, and the amount of new material published was so vast, that what was emerging was actually a new book, even if a core of material that had retained its relevance, was retained from the former work. It is for this reason that the title of the present work has been altered, even though the major topic has remained unchanged.

In a book of this nature, the author is continuously faced with the problem of deciding what general information should be included in what is destined to be a specialized account of agriculture of dry lands. Whilst the basic principles of agricultural practice are universal, an effort has been made to stress what is specific and unique to agriculture in dry regions.

A vast array of literature was perused in the preparation of the text, and a synthesis of the results of research and available information was attempted in the light of the author's own experience, after half-a-century of work in research and development in a dry region.

Only a small proportion of the literature consulted has actually been cited in the text. The references that are quoted are either in support of general principles, or are chosen as appropriate examples to illustrate these principles.

Several excellent books and reports from symposia and workshops on different aspects of agriculture in dry regions have been published since the 1970's. They are all written by experts for other experts. To the best of my knowledge, this is the only work by a generalist (an almost extinct species), that attempts to encompass the entire subject and provide an up-to-date, comprehensive, and yet concise, review of present knowledge on agriculture of the world's dry lands. Agronomists, research workers, extension workers and farmers, who live and work in the dry regions and who must cope with the complexity of the problems with which they are faced, are the primary clientele group. It is also hoped that students who are preparing for a career in these regions will find the book a useful aid in their studies.

In a way, specialists may also find interest in this work, not in their own discipline, but as a relatively easy and concise way of acquainting themselves with the state-of-the-art in associated fields. Increasing specialization, with each discipline using its own vocabulary, has created communication problems, whilst the need for multidisciplinary teams makes inter-discipline communication indispensable.

In a work of this scope, it is almost inevitable that errors of omission or commission should intrude. Quite possibly, some important aspects may have been overlooked, and there will assuredly be justification for criticism and comments. These will be welcomed by the author.

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The author is not, and could not possibly be, an authority on all special fields which this work encompasses. A number of chapters have therefore been reviewed by several colleagues, each a recognized authority in his special field, whose critical and constructive comments the author gratefully acknowledges: Dr. H. Bielorai (Plant–water relationships); Prof. A. Blum (Plant breeding); Dr. Y. Dan (Soils); Dr. M. Horowitz (Weeds); Prof. U. Kafkafi (Plant nutrition); Prof. G. Loewenstein (Plant diseases); Dr. Mantell (Irrigation); Dr. Z. Plaut (Plant physiology); and Prof. E. Swirsky (Insects).

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Ramat Gan, 1992

I. Arnon

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PART I

Environment and Natural Resources

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CHAPTER 1

Dry Climates and their World Distribution

Classification of dry areas

Major classification systems

The word arid (from 'arere' to be dry) implies a deficiency of rainfall as the basic characteristic of a dry climate. Hence, the earliest attempts to classify dry climates were generally based on the annual amounts of rainfall.

However, the amount of rainfall in dry regions cannot serve as an adequate measure of aridity unless it is related to its effectiveness, which in turn depends on many factors (cf. p. 41).

Classification of dry climates by various workers has been based on indices that range from simple combinations of precipitation with temperature, with evaporation, with relative humidity; on length of dry season or growing season; and on types of vegetation. More recently, models have been developed ranging from precipitation – ET ratio to more complicated soil–plant–atmosphere models (Meher-Homji, 1980).

A detailed description of all the classification systems proposed in the literature or even those widely used would be beyond the scope of this book; we will describe briefly some examples of the different approaches mentioned above.

The Köppen system of climates (Köppen and Geiger, 1936)

Köppen considered vegetation to be the best expression of the totality of a climate; his criteria for determining climatic boundaries were suggested with vegetation units in mind (Meher-Homji, 1980). This is the best known system, and has gained wide acceptance because it is based on relatively simple values that can be measured or estimated with sufficient accuracy in most regions of the world, namely rainfall (amount and distribution) and temperature. This makes it useful for a general comparison of climatic resources and constraints of the various land utilization types (Vinck, 1975). It assumes that: (a) the higher the temperature, the greater the amount of precipitation that will still result in the same degree of aridity, and (b) relatively less precipitation is needed if it is concentrated during the cool season, more is required

if distribution throughout the year is uniform, and the highest requirement is associated with precipitation that is concentrated in the warm season.

Köppen first defines five major categories of world climate, of which one only – comprising those regions in which the average precipitation is deficient in relation to evaporation – is termed dry.

The dry climates are subdivided into *deserts* (or arid climates), in which rainfall is insufficient for arable crop production, and *steppes* (semi-arid climates), in which rainfall is sufficient for certain types of crops when adequate management techniques are adopted and grasses constitute an important element of the native vegetation. A further subdivision is based on seasonal distribution of rainfall, according to whether the greater part of the annual precipitation occurs during the six cooler months of the year (winter precipitation) or during the six warmer months of the year (summer precipitation). Otherwise, it is considered that there is no distinct season of rainfall.

A final subdivision is based on temperature: *hot* dry climates and *cool* dry climates, according to whether the mean annual temperature is above or below 18°C, respectively.

Since latitude is the principal determinant of temperature, the drylands are classified as: low-latitude (or hot) deserts and low-latitude (or hot) steppes, and middle-latitude (or cool) deserts and middle-latitude (or cool) steppes.

De Martonne

De Martonne (1962) attempted to find an empirical relationship between precipitation and temperature, that would enable a more accurate and general definition of dry climates. This relationship is expressed in his '*aridity index*', which can refer to a selected period of a few days, a month, a season, or an entire year,

$$I = \frac{np}{t + 10},$$

where I is the aridity index, n is the number of rainy days, p is the mean precipitation per day, and t is the mean temperature of the selected period in °C.

When calculated on an annual basis, $I < 20$ is characteristic of an arid climate and $20 < I < 30$ defines a semi-arid climate.

Gaussen

Gaussen (1954), from studies of natural vegetation, developed a classification of climates based on the number of arid months in a year. A month is considered arid if $p < 2t$, where p = mean monthly precipitation (cm) and t = mean monthly temperature (°C). This classification gave good results when applied to Mediterranean climates, but was found less satisfactory when applied on a worldwide scale (Wallen, 1966).

Thornthwaite

Thornthwaite (1948) improved on Martonne's approach by introducing the water balance concept in his classification system.

He based his classification of climate on two elements: (a) water supply in the form of precipitation, and (b) water needs resulting from evapotranspiration. Precipitation and evapotranspiration are due to different meteorological causes and may be markedly different from each other both in quantity and in seasonal distribution. In principle, Thornthwaite defines a climate as moist when precipitation exceeds evapotranspiration; a *dry climate* occurs where evapotranspiration is markedly in excess of precipitation.

Thornthwaite further differentiates between *actual evapotranspiration*, which in an arid climate may be very low simply because the moisture supply is limited, and *potential evapotranspiration*, or 'water need', which is the amount of water that would be transpired and evaporated under ideal conditions of soil moisture and vegetative cover. The amount of potential evapotranspiration being dependent only on climate, by comparing it with precipitation Thornthwaite developed a classification system for arid climates. In Thornthwaite's method, potential evaporation is computed by an empirical formula involving mean monthly temperature and average daylength. When the monthly curves of potential evapotranspiration and rainfall are plotted as smooth curves, and the two curves are compared, it is possible to determine if and when precipitation exceeds evapotranspiration (Fig. 1.1).

When precipitation is adequate to supply the water that is needed for potential evaporation, the 'moisture index' is considered as equal to zero; moist climates have positive values and arid climates have negative values of this index.

The values of other important factors influencing evaporation – such as wind, humidity, and solar radiation – are considered to be linked with the variations in temperature and were therefore omitted from the formula, in order to simplify the method without affecting its usefulness.

Virmani et al. (1978), after evaluating seven important climatic classification systems, concluded that those using precipitation and potential evapotranspiration (PET) as criteria have a definite advantage, because these two parameters are of primary importance in the evaluation of the water balance of an area. It is the water balance which is a major factor in rainfed agricultural production in the semi-arid areas. Thornthwaite's values were, however, found to underrate water losses in the tropical regions where dry seasons are commonly more intense than in North America (Grove, 1980).

Modifications of the water balance system

Subsequently, a number of modifications of Thornthwaite's approach have been proposed.

Meigs. Meigs (1953) prepared a basic map of the distribution of semi-arid and arid

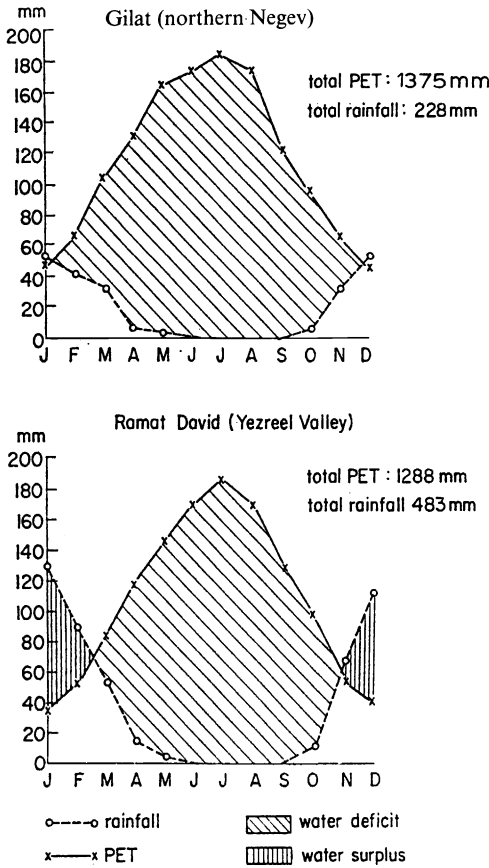


Fig. 1.1. Comparison of seasonal precipitation (R) and potential evapotranspiration (PET): annual march of R and PET through the year at two contrasting regions of Israel: Gilat (northern Negev, above) and Ramat David (Yezreel Valley, below). PET was calculated according to Penman's formula.

zones in the world based on degree of aridity (extremely arid, arid, and semi-arid) using Thornthwaite's 'moisture index', as follows:

	<i>Moisture index</i>
extreme arid climate	–57 or outer limit
arid climate	between –40 and –57
semi-arid climate	between –20 and –40

The outer margin of the semi-arid region, –20, is approximately the outside limit beyond which inadequate precipitation is not the main agricultural risk; the dividing line between semi-arid and arid, –40, separates lands where rainfed arable cropping can still be attempted with appropriate dry-farming techniques, from those in which

the risk of aridity is too great. In the extreme arid climate, at least twelve consecutive months without rainfall have been recorded and there is no regular seasonal rhythm to the rainfall.

Subdivisions are based on temperature, using the means of the coldest and warmest months, in the following ranges: below 0°C; between 0 and 10°C; between 10 and 20°C; between 20 and 30°C; and above 30°C.

A further subdivision is based on season of precipitation, as in Köppens' classification.

The *cold deserts* of Alaska, Siberia, and the western part of the Tibetan plateau, are excluded by Meigs. These are the areas where the mean temperatures in the warmest months are less than 10°C, and where even irrigation cannot ensure a reasonable level of productivity.

The Troll system. Troll (1965) proposed a classification called the Seasonal Climates of the Earth. His system is based on two main variables – thermal and hygric. The emphasis is on the duration of dry and humid months rather than an assignment of climatic boundaries based on annual values of precipitation, temperature and humidity. A humid month is defined as a month in which the mean monthly rainfall exceeds PET.

According to Troll the tropical areas are classified as follows:

tropical rainy	7 to 12 humid months
tropical wet-dry	4½ to 7 humid months
tropical dry	2 to 4½ humid months
tropical semi-desert	less than 2 humid months

This classification has been found satisfactory to explain vegetation zones of Tropical Africa and South America. The International Crops Research Institute for the Semiarid Tropics (ICRISAT) has adopted the climatic classification proposed by Troll as the working definition for defining its world mandate region.

Hargreaves. In this classification, the risk factor is taken into account by using a probabilistic rainfall value instead of the usual monthly average. Hargreaves (1971) developed a 'moisture availability index' (MAI), defined as the ratio of monthly precipitation at the 75% probability level, to monthly PET. Areas with three to four consecutive months with a MAI > 0.33 are defined as semi-arid, and suitable for growing crops requiring a growing period of three to four months.

Bailey. Instead of using potential rates of evapotranspiration (PET), Bailey (1979) prefers to use actual evaporation (AE) for measuring the effectiveness of rainfall, because "comparisons of actual transpiration are of more significance to agriculture than rainfall, for evaporation indicates the amount of water available for transpira-

tion, i.e. for plant functions". Accordingly, he developed the *Bailey moisture index* (S),

$$I=S/6.37,$$

in which I is a ratio expressing precipitation as a proportion of optimal evaporation (OE), which is about 80% of the maximum evaporation. Precipitation that is responsible for (OE) is termed by Bailey as optimum precipitation (OP).

A month in which rainfall is sufficient to allow OE is classed as adequate in precipitation, and evaporation as low as 81% of OP is still sufficient to keep the month in neutral position with respect to moisture adequacy.

If monthly evaporation is less than 81% of OP, the month is rated as dry. At least three consecutive months above the 81% level are deemed necessary for the success of grain crops.

UNESCO aridity index. UNESCO (1977) has defined a number of bioclimatic zones based on an aridity index: P/PET (P =precipitation, PET =potential evapotranspiration). Four types of dry regions were identified:

- *Hyperarid* ($P/PET < 0.03$): deserts void of vegetation, excepting ephemerals and shrubs in river beds.
- *Arid* ($0.03 < P/PET < 0.20$): dryland areas with sparse perennial and annual vegetation used by pastoral systems.
- *Semi-arid* ($0.20 < P/PET < 0.50$): steppe or tropical shrubland; dryland farming widely practised.
- *Subhumid* ($0.50 < P/PET < 0.75$): more dense vegetation, rainfed farming widely practised; crops adapted to transient drought.

According to Hatfield (1990), the delineation of zones as defined by UNESCO is not precise, and large errors can occur in the classification of a given location.

FAO: Length of growing period. FAO (1978) has attempted to refine the UNESCO system, by basing its classification of dry climates on the growing period. The latter is defined as the number of days during the year when $P > 0.5 PET$, plus a period over which an assumed 100 mm of water stored in the root zone from excess precipitation (or less) could be used.

Days during which temperatures are too low for growth (mean $t=6.5^{\circ}\text{C}$) would be excluded from the computation. Using this system, areas are classified as follows:

- *Dry*: no days with $P > 0.5 PET$, no growing period;
- *Arid*: growing period of 1–74 days;
- *Semi-arid*: growing period of 75–119 days.

Conclusions

The classification of climates into world systems and large regional systems and their characterization should facilitate the transfer of knowledge, experience, and successful technologies from one part of the world to other regions. Their usefulness would be compounded if used together with other worldwide systems, such as soil resources (cf. Ch. 3) (Vinck, 1975). However, none of the classifications that have been developed is ideal in the sense that it is simple and complete.

Furthermore, a major limitation of all these systems in relation to dry climates is that the latter have, as a major characteristic, considerable variability. These climates are controlled by complex atmospheric processes which are easily disturbed by minor changes in air movement, ocean currents and temperatures. In consequence, weather parameters and precipitation, in particular, fluctuate considerably around mean values, both in time and in space.

Subramaniam and Sastri (1969), in an analysis of a 75-year period, found that 39 years were on the dry side and 37 on the wet side; they concluded that the definition of a climatic zone would vary from year to year.

Walton (1969) cautioned that the highly variable rainfall in arid regions makes nonsense of mean annual rainfall statistics, and thus would affect the interpretation of any climatic index. Under these circumstances, the mean values on which all classification systems are based lose much of their significance.

The borders between climatic zones are therefore ill-defined and furthermore, change continuously. Disregarding these fluctuations has been the cause of major disasters, such as the dust bowl of the 1930's in the USA, and of desertification of large areas in more recent years (cf. Ch. 15).

In order to relate climatic factors to land use systems and management practices as discussed in this book, we have adopted the following pragmatic working classification as the most meaningful for our purpose, with due consideration given to its limitations.

Types of dry climates

The major types of dry climates in terms of their location and thermal regimes are: (a) *arid* (or *desert*) climates with insufficient precipitation for normal crop production and (b) *semi-arid* climates in which a dry season alternates with a wet season.

There are three basically different semi-arid zones:

- the tropical and subtropical frost-free savannah climate with summer rainfall;
- the middle-latitude steppe continental climate with definite warm and cold seasons and mostly summer rainfall;
- the Mediterranean climate, with mild winters, occasional frosts, winter rainfall and hot summers.

All three types of semi-arid climates have fringe areas of relatively low mean annual

precipitation. Because of the great variability of rainfall that is characteristic of these areas, cycles of years with sufficient precipitation for crop production alternate with cycles when insufficient precipitation causes crops to fail. These are the most hazardous areas for rainfed agriculture.

Arid (or desert) climates

For the purposes of this book, arid climates are those in which no arable crop can be grown, unless precipitation is supplemented by water harvesting and spreading, or by irrigation. They are deserts in the full sense of the word, and as such their agricultural potential, at best, is confined to livestock production under extensive conditions.

The upper limit of 250 mm is generally used to characterize arid climates (Fuchs, 1973) (a higher limit, 400–500 mm, is justified in summer rainfall areas). Rains are rare and completely unpredictable. Only rarely will they suffice for arable cropping without additional water, excepting possibly in favoured niches, such as depressions, sabhas, water courses, etc. Several years may sometimes elapse without rains. The occasional rains may be of high intensity and cause floods.

Solar intensities are very high, excepting when a high dust-laden atmosphere reduces the intensity of solar radiation.

The ability to survive under desert conditions is an essential characteristic of the xerophytic natural vegetation of the arid regions. Typically, many of these plants have adapted themselves to arid conditions by a reduced transpiring surface resulting in dwarfed plants with very limited leaf surfaces (cf. Ch. 6).

The traditional land use of the world's deserts has been pastoralism, and in its modern form – ranching.

Hot arid climates. These comprise deserts and semi-deserts with less than two humid months. Nomadic pastoralism is the dominant land use. Game is a resource that can be a source of income, either as a tourist attraction, and/or for systematic harvesting (cf. Ch. 8).

Cool arid climates. Middle-latitude deserts are located either in regions that are remote from oceans or are on the leeward side of mountains (cf. pp. 33, 34). These are typically continental climates found chiefly in parts of the USA, Canada, Siberia and Argentina. These climates are characterized by long cold winters, cold soils, short growing seasons, high summer insulations, high daytime temperatures in summer, and by potential evaporation exceeding precipitation for much of the growing season (Thorne and Thorne, 1979).

Cold arid climates. The cold deserts, in which the mean temperatures in the warmest months are less than 10°C, and where even irrigation cannot ensure a reasonable level of productivity, are not included in the scope of this work.

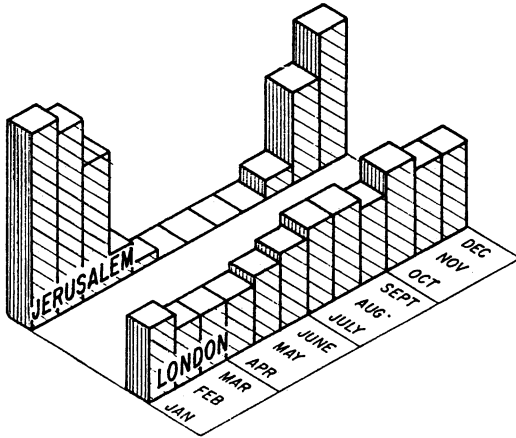


Fig. 1.2. Typical seasonal patterns of rainfall distribution in semi-arid (Jerusalem) and humid (London) climates with approximately the same annual precipitation rates (averaging 600 and 620, respectively).

Semi-arid climates

On the poleward fringes of the hot deserts are transitional climatic zones; on the equatorial side are seasonally dry tropical regions with high temperatures, which enjoy some of the hot-season rainfall of the tropics; on the west coasts are the subtropical regions with completely dry summers and cool moist winters – the Mediterranean climates. Eastwards, in the middle latitudes, lie the cool, dry, temperate regions with very cold winters and continental rainfall.

The term semi-arid can be misleading, in that it implies a climate that is intermediate – between dry and humid – in the amount of precipitation received.

Actually, semi-arid climates are *seasonally arid*, and are characterized by a completely dry season that alternates with a more or less humid season, in which the amounts of precipitation may well exceed the amount typical of a humid climate. For example, Jerusalem, with its semi-arid climate, has an average annual rainfall of 600 mm, which is practically identical to that of London (620 mm); the former has a completely dry season of six to seven months, whilst the latter has a humid climate practically the whole year (Fig. 1.2).

The contrast is even greater if we compare rainfall in a temperate climate with that characteristic of the semi-arid tropics. Low-rainfall regions in India have an annual average precipitation of 500 to 900 mm (Venkateswarlu, 1984), whilst the more humid semi-arid areas have up to 1250 mm (Willey et al., 1989). Paradoxically, above-average rainfall can have a more negative impact on yields than below-average rainfall.

A more appropriate name for these climates would therefore be ‘seasonally dry climates’. However, in order not to add to the plethora of continuously changing

terminology that plagues the readers of professional literature, we will continue, for the sake of convenience, to use the customary term semi-arid.

During the dry season, crop production is only possible if water has been stored in the soil during the rainy season, or if irrigation is provided.

Hot semi-arid climates (savannah zones). These semi-arid regions are characterized by a dry season of four-and-a-half to seven months and a wet season with an annual precipitation of 500 to 1500 mm; rainfall is very variable, and often very intense, causing severe problems of soil erosion. Atmospheric demand for water is very high; coupled with low and variable rainfall, periods of transient drought occur frequently. Only during the rainy season is PET exceeded by precipitation, and recharge of soil moisture reserves becomes possible (Kanemasu et al., 1990).

On the basis of temperature, the semi-arid tropics are warm throughout the year and suitable for the production of any crop that does not require a cold period in its lifecycle. Unreliable moisture is the key limiting factor (Virmani et al., 1980).

Kanemasu et al. (1990) distinguish between a wet-dry semi-arid zone, in which the growing season may extend from 150 to 210 days, and a dry zone with a growing season of 60 to 150 days. Average annual precipitation varies from 500 to 1200 mm, and PET values range from 1200 to 2000 mm.

The reliability of rainfall at the beginning of the season is generally low, and consequently there is a high degree of risk in establishing crops, because there are no soil reserves of moisture at this time.

Mediterranean-type climates. At latitudes of around 30° to 40°, on the west sides of the continents, are located the areas with a Mediterranean-type climate. In terms of latitudinal locations and temperatures, this is a subtropical climate, being dry in the summer and cool and wet in the winter. In summer, all the winds and high-pressure belts 'move polewards with the sun', and as a result the dry regions extend to the higher latitudes, up to 40° – hence the dry summer which is characteristic of these lands. In winter, when the sun 'retreats towards the Equator', the high-pressure and wind belts receive occasional rain – hence the moderate winter rainfall.

Mediterranean climates are found in the regions bordering on the Mediterranean Sea, in central California, in central Chile, along a narrow coastal plain near the south-west tip of Africa, and in small areas in western and southern Australia.

The Mediterranean climate is characterized by mild winters and hot, but not oppressive, summers. Frosts and snow are rare. Rainfall is light to moderate, and generally occurs in heavy downpours. Sunshine is abundant even during the winter months.

Cool semi-arid climates (middle-latitude steppe zones). Parts of the cool dry climates have a precipitation that is sufficient for growing crops, ranging from 250–

300 mm (which permits growing a cereal crop in alternate years, by using a crop-fallow rotation), to 500–550 mm, enabling annual cropping.

The absence of frost delimits the equatorial boundary and cool summers the poleward limit of the steppe areas. Rainfall is mainly in summer, but a significant part of the precipitation is in the form of snow, which, on melting, contributes water to the soil or to the aquifer. Precipitation may vary considerably over short distances.

Strong winds and dust storms are a frequent occurrence in summer, and severe blizzards blow snow in the winter. The growing season is about 120 to 140 days, and is frequently shortened by unseasonal frosts. Grass is the dominant vegetation.

Farming of the extensive steppe areas of North America and Eurasia was initiated at the beginning of the 19th century (Bowden, 1979). The major concern of the farmers is to make the most of the short growing season, and optimal conservation and utilization of water.

Lack of significant land mass explains the rare occurrence of steppe lands in the southern hemisphere, excepting for relatively small areas in Argentina, south Australia, and southeast Africa (Bowden, 1979).

Moisture regimes. In each of the semi-arid regions outlined above are a number of distinct moisture regimes, as follows:

Fringe semi-arid areas. On the fringes of the deserts are areas with an average precipitation of less than 200–250 mm (winter rainfall), or an equivalent 400–500 mm in summer rainfall areas, amounts that are barely sufficient for crop production. These are typically either steppe or savannah areas which, in their natural state, had a permanent vegetative cover.

It are these transitional zones that are areas of high drought risk in all parts of the world (Newman and Pickett, 1974). Because of the considerable variability of precipitation from year to year, which characterizes these areas, precipitation in most years will be insufficient to produce a crop, and, occasionally or cyclically, years occur in which precipitation enables barely satisfactory yields. Generally, high moisture stress prevails during the entire season. The amounts of water available for production in these fringe areas suffice only for a limited growth period. Therefore, the only possible way to achieve an economically sustainable agriculture in these low-rainfall areas is to develop and apply methods for increasing available soil moisture and reducing water losses to a minimum. Experience has shown that this can be achieved by conservation tillage, crop-fallow systems, water harvesting, mulches, weed control, etc.

Semi-arid areas with adequate average rainfall. Annual average precipitation in these areas is above 350–400 mm in winter precipitation, and an equivalent 1200 mm and above in summer rainfall. Adequate average precipitation implies that there will be some seasons with too little moisture for optimal yields, but years of drought, i.e., years of crop failure, or near-failure, are relatively few. In average and above-average

years, a favourable water supply will enable a crop to express its full yield potential. However, in the occasional years of much higher than average precipitation, yields may be depressed because of waterlogging, delayed harvest, incidence of diseases, etc. Soil erosion hazards are also increased.

The two major moisture regimes under which arable crops are grown in areas with adequate average rainfall are (a) on stored water in the dry season or (b) in a variable and unpredictable moisture environment during the rainy season.

(a) *Stored moisture environment.* In all semi-arid regions, whether subtropical, Mediterranean or middle-latitude, crops can be grown during the dry season, completing their entire life cycle on precipitation stored during the preceding rainy season.

At the time of planting, the farmer knows the amount of available soil water, so that he can choose appropriate management practices. These will be mainly aimed at minimizing ET during vegetative growth, so as to ensure an adequate moisture supply for the reproductive stage (cf. Ch. 15).

(b) *Variable moisture environment.* In this environment, crops are grown during the rainy season (winter crops in Mediterranean climates, summer crops in subtropical and middle-latitude climates). Sowing is either in dry soil, shortly before the expected onset of the rains (modern farming), or shortly after the first rains have wet the soil (subsistence agriculture). Even in years of above-average rainfall, occasional periods of drought occur during the growing season. Plants must be able to take advantage of the periodic rainfall, and to recover quickly from periods of intermittent stress, at whatever stage they occur.

The dry regions of the world

Africa

Northern Africa is characterized by the unusual longitudinal breadth of the dry regions and their extension towards the Equator, in contrast to the situation south of the Equator. As a consequence, in Africa, transitional wet-and-dry climates are much narrower on the northern side of the Equator than on the southern side (Trewartha, 1961).

The dry areas of Africa comprise three categories: hyperarid, arid and semi-arid; the criterion used to separate these categories is the ratio of annual precipitation to evapotranspiration (UNESCO, 1977).

The hyperarid zone (area about 6.5 million km²) comprises the vast Sahara region, the north coast of Somalia, and the coast of south-west Africa. The arid zone (6.1 million km²) is located on the margins of the former; the semi-arid zone (4.8 million

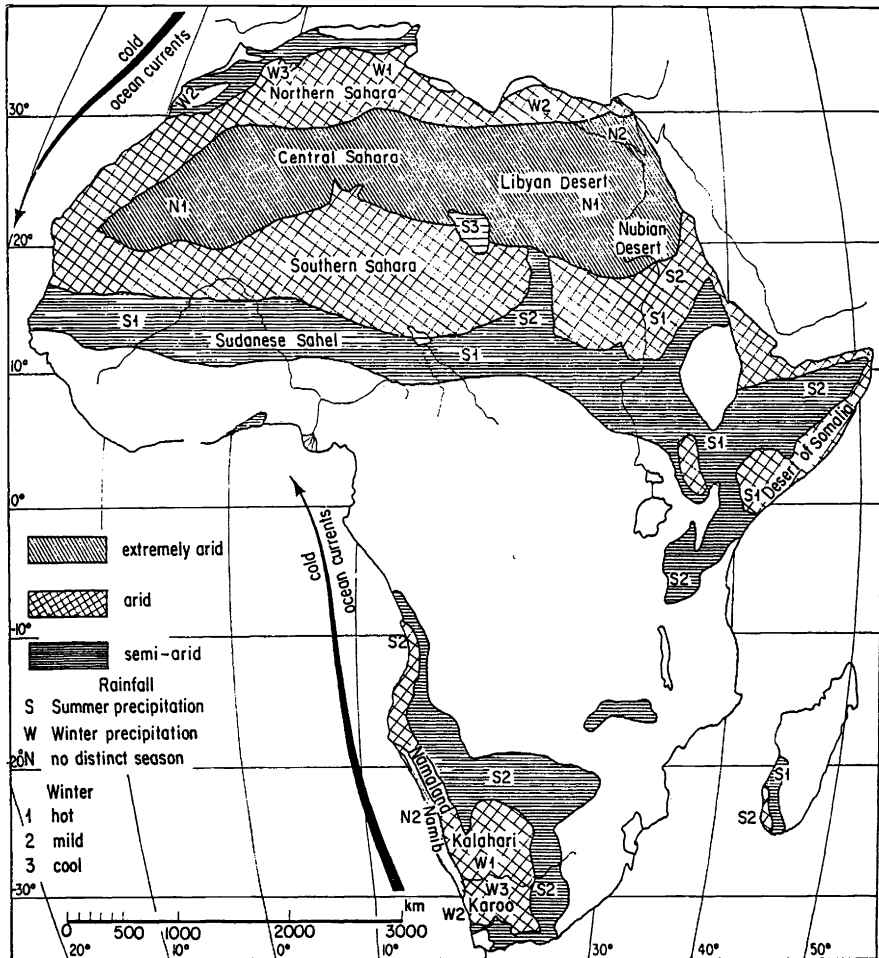


Fig. 1.3. Map of the arid and semi-arid regions of Africa. (After Meigs, 1953). © UNESCO, 1953. Reproduced by permission of UNESCO.

km²) surrounds the drier zones and extends out from them to various distances, depending on topography (Ayensu, 1985).

The Sahara and its margins

The Sahara is the largest desert of the world and extends practically across the African continent between approximately 15° and 33°N, covering some 9 million km². In reality the Sahara is only a part of a still larger area of dry tropical-subtropical climate, extending from the Atlantic Ocean across northern Africa, Arabia, and western Asia, to northwestern India-Pakistan (Trewartha, 1961) (Figs. 1.3 and 1.4).

The Sahara is in the trade-wind belt: dry north-east winds prevail over major

sectors, becoming hotter and drier as they cross the landmass. In the Sahara are large areas of barren, shifting sand, as well as stony wastes, hills and mountains, valleys and depressions. There are also a number of oases, the largest of which is the narrow valley of the Nile.

There is a great range in diurnal as well as annual temperatures, and frosts may occur in the winter months. The intense heating by day, contrasted with the cooler nights, results in strong winds during the day and generally calm nights; dust storms are frequent. The greater part of the Sahara has less than 100 mm of annual rainfall, mostly occurring in heavy showers. The central, extremely arid core, comprises the Central Sahara, the Libyan Desert, and the Nubian Desert. These are bordered by the less dry deserts: the northern Sahara, with a rainfall not exceeding 200 mm and occurring in winter, and the southern Sahara, with rainfall occurring in summer.

On the northern fringe of the Sahara is a narrow strip of steppe, stretching across Morocco and Algeria, and marking the transition between the desert on one hand and the coastal strip with a Mediterranean climate on the other.

The Sudano Sahel

South of the Sahara is a savannah belt which is subdivided into ecologically distinct zones, in which rainfall increases steeply southward (Tiessen, 1988):

	Mean annual precipitation	Land use
The most northern belt	< 350 mm	extensive nomadic grazing
The Sudan savannah	400–900 mm	grazing and millet (<i>Penisetum</i>) production
The Guinea savannah	900–1300 mm ^a	diverse crop production

^aRainfall unreliable; years of less than 900 mm are common.

The rainy season is monomodal, from May/June to September/October. Rain intensities are high, and often exceed 100 mm/hour. Storms are often followed by hot days with high evaporative demand, resulting in the rapid dessication of the soil surface (Hoogmoed and Klaij, 1988).

The arrival of the monsoon in the southern Sahel occurs in late April, May, or June and moves northward to the drier latitudes verging on the Sahara in July, August, and September (Kanemasu et al, 1990).

The beginning of the cropping season is marked by the first rainfall that is sufficient for crops to germinate. The length of the growing season is determined by the time between this first useful rainfall and the end of the rainy season, though transient droughts during this period can occur (Dancette, 1980).

Temperatures and evaporative demand are high during the monsoon growing season.

There is no precise boundary of the semi-arid zone to the south. It gradually merges into the humid savannahs and forests, characterized by a wet season that exceeds the dry season in length.

This Sudanese Sahel includes portions of the territories of Senegal, Mali, Upper Volta, Mauritania, Ghana, Niger, Togo, Dahomey, Nigeria, Cameroun, Chad, and Sudan.

Along the east coast of tropical-equatorial Africa, between about 12°N and 2–3°S of the Equator, is a dry region, comprising the desert of Somalia, eastern Ethiopia, and northeastern Kenya (Fig. 1.3). The aridity of this region is considered by Trewartha (1961) to be a 'climatic abnormality', because an equatorial dry climate along an eastern littoral is unusual. In such a latitudinal and geographical location a tropical humid climate generally prevails. The situation of this region on the windward side of the continent, with highlands rising abruptly interior to the coast, would also appear to warrant greater precipitation than is actually received.

South of the Equator in East Africa the water deficiency is generally not as severe as it is in corresponding regions to the north. Only a small area in eastern Kenya is really desert. However, semi-arid climates with unreliable rainfall are widespread, both along the coast and in the interior.

Southern Africa

According to Trewartha (1961), the most striking climatic peculiarity in Southern Africa is the large proportion of the total area in which dry and semi-arid climates predominate (Fig. 1.3).

Desert conditions prevail along the coast of southwestern Africa, from Angola to the Cape Province. Whatever rain does occur falls in summer in the north, and throughout the year in the south.

This region comprises the extremely arid Namib Desert, and the less dry Namaland, Kalahari, and Karoo, covering some 550 000 km² in all.

The Namib Coastal Desert belongs to the class of deserts which are extremely dry as a result of being located along the tropical and subtropical western littorals bordered by cool ocean currents and colder upwelled water (Trewartha, 1961). The cold currents off the shore cause frequent fogs, high air humidity, and relatively mild temperatures, and yet the Namib Desert is characterized by intense aridity. In a narrow coastal strip some 30 to 50 km in width extending over a latitudinal stretch of about 15°, the annual rainfall is under 125 mm. The lowest precipitation coincides with the coastline and there is a slow increase inland (Trewartha, 1961).

Two-thirds of the Republic of South Africa are in the arid or semi-arid area consisting of four main plateaux (Dyer, 1955):

The Coastal Plateau – ranging from sea-level to 300 m elevation, with a winter rainfall of up to 120 mm. A cold ocean current flowing up the coast causes fogs and heavy dews.

The Second Plateau – with an elevation of 300 to 600 m, is surrounded by mountains. The western part is the Little Karoo, with a rainfall of 150 to 200 mm.

The Third Plateau – to the north of the former, has an elevation of 600 to 900 m and is called the Great Karoo. It has 120 to 200 mm of rainfall, mostly in winter.

The Central Plateau – is a large inland area with an elevation of 900 to 1500 m, called the Upper Karoo. The rainfall averages 125 to 500 mm, mostly in summer precipitation. Winters are cold, with frequent night frosts. Grazing is the predominant land use (Walter, 1962).

To the north, the central plateau descends into the Kalahari sand veld.

Eurasia

Eastern Mediterranean region

This region, formerly known as the Levant, comprises Syria, Lebanon, Israel, and Jordan.

Along the sea coast, the climate is typically Mediterranean, with a regular pattern of winter rains (late October to May), and an absolute summer drought. Eastwards, mountain ranges parallel to the coast partially prevent the moisture laden winds which originate in the Atlantic, from spreading inland; therefore rainfall declines rapidly, from an annual average of over 500 mm, to less than 200 mm inland, over relatively short distances. Rainfall also declines from the North southwards, but the decline is more gradual. Both eastwards and southwards the semi-arid climate merges into full deserts.

Along the coast the winters are mild; frosts and snow are rare. The climate is more extreme in the mountains, and becomes semi-tropical in the Rift valley.

Because of the coastal ranges, most of the perennial streams drain inland. For example, the Jordan terminates in the Dead Sea. The majority of the streambeds occasionally convey raging torrents in winter and dry up completely in winter.

South-west Asia

South-west Asia has vast areas of hot desert extending from Arabia to western India (Fig. 1.4). Most of Arabia is a hot and barren desert plateau covering approximately 2.5 million km²; it has very little rainfall and what there is occurs mainly in the winter months. The northern part is a stony or sandy desert producing some pasturage; in the centre are mountain chains with alluvial cultivated valleys, whilst the south is in the rain shadow of these mountains and is therefore extremely arid desert (the Rub el Khali). In the region between the lower Tigris and Euphrates is a hot desert which was once widely irrigated. The scanty precipitation occurs in winter. The region has rich alluvial soil, and was extensively cultivated in the past. Only a small part is cultivated at present; the reasons for the decline that has occurred are described in Ch. 8.

In the southern half of Arabia is a highland region bordering on the Red Sea coast that has a warm, semi-arid climate with prevailing summer rains. A second highland strip in south-east Arabia, near the Gulf of Oman, has a similar climate.

Middle-latitude dry climates of Eurasia

A highland area including northern Iraq and Syria and most of Asiatic Turkey extends from Anatolia to the Iranian plateau. The area has short dry summers, long cold winters, and scanty rainfall – most of which falls in winter (Fig. 1.4).

The Iranian plateau itself, lying between the Indus and the Tigris valleys, is surrounded by mountain ranges with scanty precipitation – mostly falling in the winter months and including a fair amount of snow.

In southwestern Afghanistan and northwestern Baluchistan are desert plateaux and hilly steppe regions. Temperatures are very high in summer and very low in winter; humidity is low and sunshine is plentiful.

Farther to the east and north, in those parts of Eurasia which are the farthest away from oceans, between latitudes 35° and 50°, is a huge arid and semi-arid plain, stretching from the Black Sea to Manchuria. Over two-and-a-half million km² of the former Soviet Union are steppe and desert, of which the central Asian deserts account for almost two million km² (Manton, 1954). Annual rainfall ranges from zero to 150 mm in the desert, and from 150 to 300 mm in the semi-desert areas (Rode, 1955). The region comprises the extremely arid great deserts of Central Asia, including the Aral–Caspian Depression – an immense lowland, barren, cold desert – the Takla Maklan desert of Sinkiang, and the Gobi Desert of Mongolia (Fig. 1.4). These are deserts of drifting sand, with cold winters, and very hot summers having scanty precipitation.

Only two great rivers traverse the central Asian deserts: the Syr-Darya, the waters of which are used for irrigation in Uzbekistan, and the Amu-Darya, which is used for watering land in Turkmenistan (Manton, 1954).

In the desert zone within the former USSR (Serozem soil region), average July temperatures reach 26–30°C. The combination of high summer temperatures and low rainfall results in very low relative humidity (20–30% on the average) and high potential evapotranspiration, which may reach 2000 mm per year (Rode, 1955). Winter temperatures are low, but increase from north to south ranging from –12°C average minimum temperature in January in the north to –2°C in the south. However, very low minimum temperatures occur throughout the zone, and may reach –30°C even in the south.

Surrounding these deserts are extensive steppe regions comprising much of the Black Sea area, of the Volga region, of Azerbaijan, of Turkmenistan, of Uzbekistan, of Kazakhstan, of Mongolia, and of Manchuria. These regions have sparse rainfall throughout the year, with hot summers and warm dry autumns. The climate of the northern belt becomes more severe from west to east, with winters becoming longer and more severe and the snow cover thinner. Summers are too cool in the west, and

too short in the east, to justify intensive irrigation. The main characteristic of the greater part of these regions is the very cold winter, with minimum temperatures that may fall as low as 25–30°C below zero, resulting in the soil freezing to various depths. Winters are milder in the southwestern part – the Turanian depression, the Caucasus, and southern Ukraine. A considerable proportion of the Eurasian steppe region consists of highly fertile, vast alluvial plains. These result from age-old deposits from the large number of great rivers traversing the region with their tributaries, and include black earth zones and deep brown soils with a thick grass cover.

In the Russian steppes (Chernozem zone) the average July temperature fluctuates between 20 and 23.5°C. Average annual precipitation is between 300 and 450 mm, with a maximum in early summer (June) and with fairly long dry periods between rains. Another summer characteristic is the frequency of the dry and strong east or south-east winds, which may cause the relative humidity to drop very rapidly to 15–20% and the temperatures to rise to 40°C (Rode, 1955).

In the drier steppes (chestnut and brown soils zone) the average precipitation is 250–350 mm, with one-quarter to one-third falling in summer. The main sources for water storage in the soil are the autumn rains and the spring snow thaw. Most of the summer precipitation evaporates, and very little run-off occurs (Vilenskii, 1957). Average July temperatures range from 20 to 25°C, and January temperatures from –7 to –17°C. In eastern Kazakhstan, minimum temperatures of –40°C have been recorded (*ibid.*).

The Indian subcontinent

Arid and semi-arid regions cover the whole of Pakistan and approximately one-third of the surface area of India. Such regions are found in all the 11 states situated in the western half of the country.

The hot arid regions of India cover about 75% of the 400 000 km² of arid lands; in the remaining area are the cold arid regions in the Ladakh area of Jammu and Kashmir State in Northwest India (Das Gupta, 1977). Part of the arid area of Pakistan and a contiguous area in India form the Thar Desert (Dakshini, 1985).

In the north it takes in the southern part of the Punjab, on the east it is bounded by the Aravalli Mountains, in the south it reaches the coast, and in the west it reaches the western border of West Pakistan. The regions comprising this arid zone include Sind, Baluchistan, all Rajasthan west of the Aravalli Mountains, the southwestern tip of Punjab (India), southwestern Punjab (Pakistan), and most of the North-west Frontier Province.

The most important source of irrigation water in this region is the Indus River system, so that most of the cultivated land is restricted to the area through which the Indus River and its tributaries flow, or in which their waters are carried by canals. The Indus plains have one of the world's largest and oldest irrigation systems, including some 12 million hectares of irrigated land, with thousands of kilometres of canals.

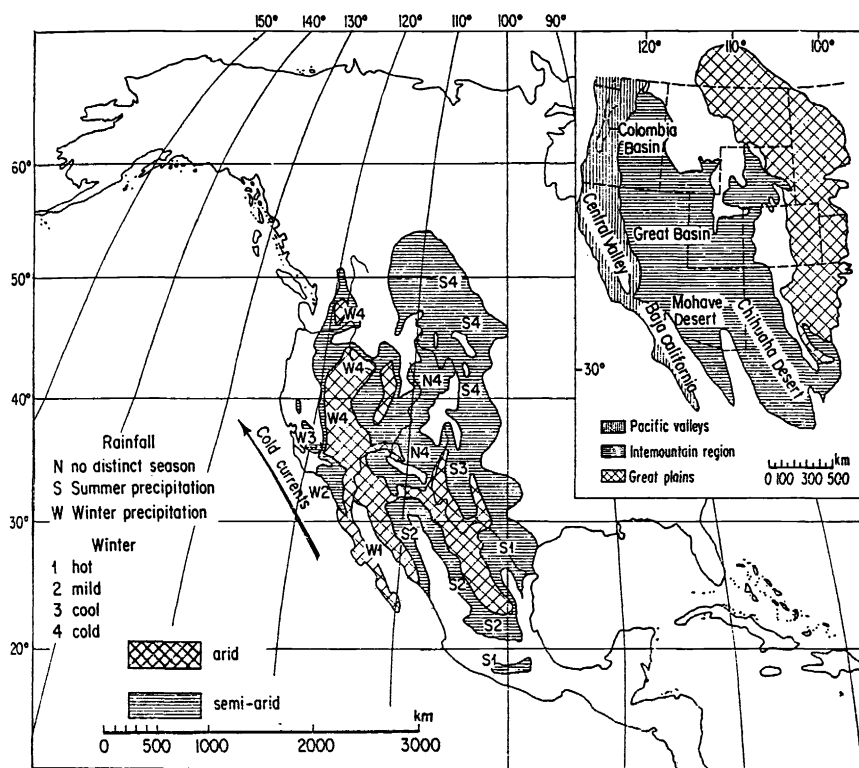


Fig. 1.5. Map of the arid and semi-arid regions of North America. (After Meigs, 1953). © UNESCO, 1953. Reproduced by permission of UNESCO.

The annual water-flow of the catchment area of the Indus and its tributaries is more than double that of the Nile (Kaser and Allison, 1967).

The Indian subcontinent is primarily characterized by a tropical monsoon climate with four seasons (Dakshini, 1985):

North-east monsoon season	December–March
South-west monsoon season	June–October (semi-arid region)
	July–September (arid region)
Transitional hot weather	April–May
Transitional period of the retracting south-west monsoon	October–November

In the arid and semi-arid regions of the subcontinent, the same seasonal rhythm prevails, but variability in space and time is much greater.

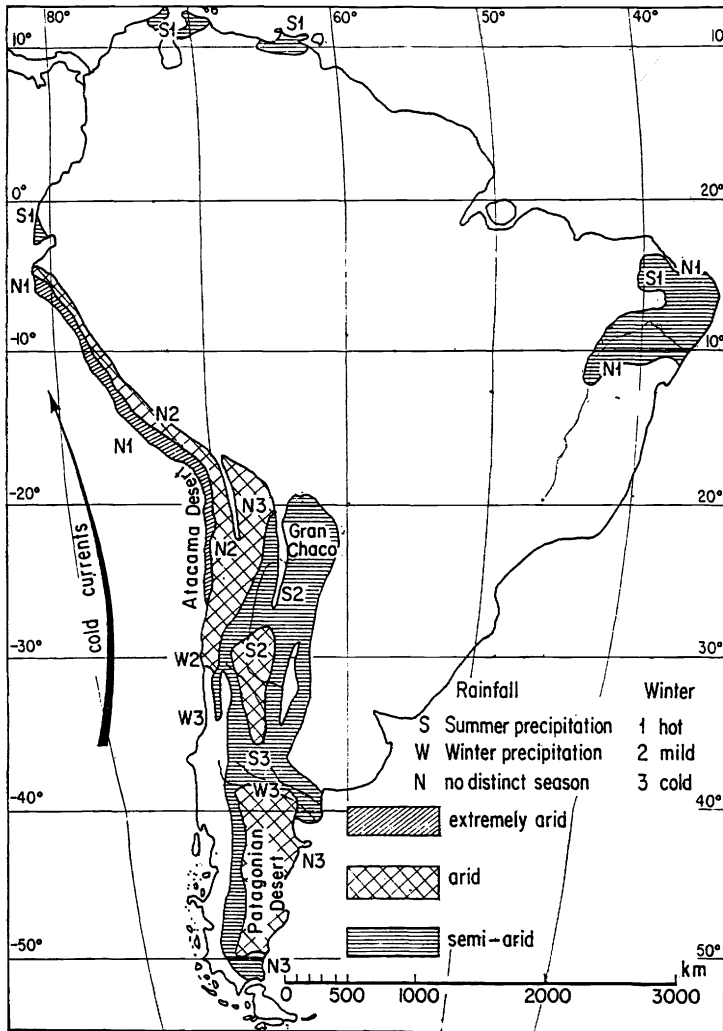


Fig. 1.6. Map of the arid and semi-arid regions of South America. (After Meigs, 1953). © UNESCO, 1953. Reproduced by permission of UNESCO.

Rainfall. Mean rainfall usually ranges from 0 to 200 mm in arid regions, and 400 to 700 mm in the semi-arid regions. The main rainy season is from June to September, during which period 90–95% of the total annual precipitation occurs, under the influence of the south-west monsoon. This is the hottest period of the year, thereby reducing the efficiency of the rain received.

On average, the maximum number of rainy days per year is 20 in the arid region, and varies from 20–50 in the semi-arid region. In addition to the main rainy season,

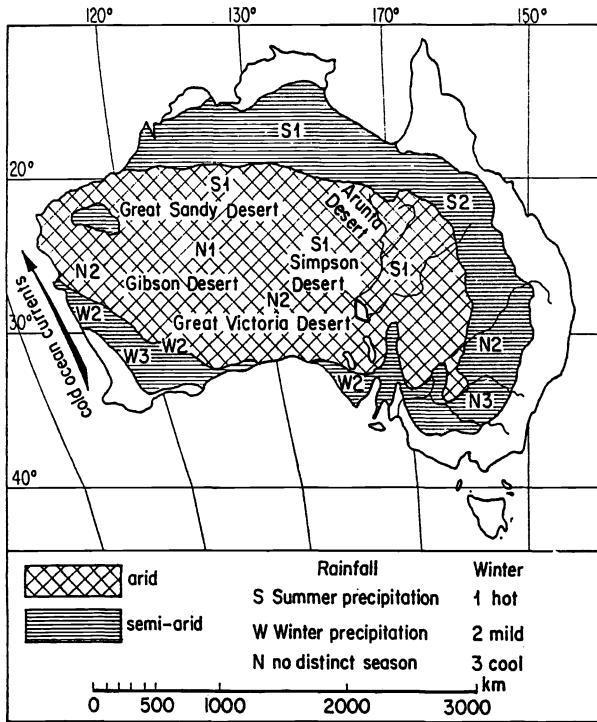


Fig. 1.7. Map of the arid and semi-arid regions of Australia. (After Meigs, 1953). © UNESCO, 1953. Reproduced by permission of UNESCO.

rainfall may occur for a few days during the cooler period of the retracting south-west monsoon, and, occasionally, during the rest of the year.

Once in 10 years, the expected annual rainfall of the arid zone of north-west India can be less than 200 mm. In some areas it may be less than 60 mm.

Air humidity. Average relative air humidity values are more or less similar in the two regions. Mean annual evaporation is 200–300 mm in the arid regions, and 200–350 mm in the semi-arid regions. Daily evaporation rates during summer exceed 12 mm in the arid regions.

Temperatures. Winters are cool, with occasional frosts. The hot season begins in early April; June is the hottest month, with daytime temperatures reaching 50°C or even higher during heat waves. The diurnal variation in temperatures in the arid regions may be as much as 11–17°C.

Winds. Hot winds are frequent during the summer months. Very high wind velocities may be recorded throughout the year, except during the post-monsoon season.

Occurrence of dust haze and dust storms is characteristic for the region. In the arid parts of Pakistan and some parts of India, dust clouds have been recorded at a height of 6000–9000 m.

China

Aridity increases steeply from the coast inland as the monsoon from the Pacific Ocean progressively loses its moisture while passing over the land mass. Drylands, ranging from subarid to superarid, account for over 40% of the total area of China, mainly located in the north-west of the country. Typical steppe characterizes a vast area, from the middle of the Shuang-Lio Plain, through the inner Mongolian Plateau, to the south-west Plateau. Its north-west border merges into semi-desert. Its south-west edge extends to the steppe of Qinghai and the Tibet Plateau.

Rainfall increases from 200 to 300 mm in the northern part of the steppe to 300–450 mm (Ren Jizhou et al., 1985).

North America (Fig. 1.5)

The dry farming areas of North America are clustered within three major geographical regions lying in the 17 western states of the USA and the three prairie provinces of Canada: the Pacific Valleys, The Intermountain Region and the Great Plains. The USA part of the Great Plains comprises three subdivisions: Northern, Central and Southern (Cannell and Dregne, 1983). The Sierra Nevada Mountain Range separates the Pacific Valleys from the Intermountain Region, whilst between the latter and the Great Plains are the Rocky Mountains.

The Pacific valleys

Pacific Northwest. The Pacific Northwest has a maritime climate that is determined primarily by prevailing westerly winds from the Pacific Ocean. Winters are cool and moist, and 75% of the precipitation occurs from November to April. In the grain producing areas, precipitation ranges from 200 to 750 mm. (Cannell and Dregne, 1983).

Pacific Southwest. The Pacific Southwest comprises California, Nevada, and Arizona. The two latter are mostly arid.

The Central Valley of California has a climate that varies from semi-arid in the Sacramento Valley in the north, to arid in the more southern San Joaquin Valley. Almost all the rainfall occurs in winter. The extreme heat and low relative humidity are the reasons for the very high evapotranspiration rates that characterize the area, which is mostly irrigated.

The Intermountain region

The Intermountain region lies in the rain shadow of the Sierra Nevada mountain

range. Summer temperatures are high; winters, whilst cold, have temperatures that are somewhat milder than might be expected at this latitude. A dominant climatic feature is the biannual rainfall variation: one maximum occurring in winter, the second during the warm season. The biannual variation in rainfall is most marked in central Arizona, with a decrease in amplitude in all directions from this centre (Trewartha, 1961).

The Intermountain Region is divided into two main sectors: the northern part is a cool desert (the so-called 'sage-brush zone') and the southern part is a warm desert (the creosote-brush zone). Within the sage-brush zone are a number of distinct sub-regions, such as the Columbia Basin in the north and the Great Basin in the centre of the region.

The sage-brush zone

The *Columbia Basin* is a high-altitude, dry plateau, though on the fringes of its arid core is a semi-arid belt that is largely cultivated with winter wheat. The Columbia River skirts around the northern and western margins of this subregion. However, because this river flows through a very deep canyon and therefore lies far below the plateau surface, the great volume of flowing water is not easily available for irrigation.

The *Great Basin* is the largest of the North American deserts; it occupies most of Nevada, the western half of Utah, southern Idaho, southeastern Oregon, and part of eastern California. It is an arid upland region with enclosed valleys and broad basins lying between high steep mountains (Jaeger, 1957).

Precipitation is mostly in winter, of which more than 60% as snow. In the northern part, winters are cold, the southern part has milder winters; the whole region has hot summers (McKell, 1985). The western part, lying in the rain shadow of the Sierra Nevada, gets the least rainfall, with annual averages of 125 mm or less. Summer showers become more frequent with increasing distance from the coast (MacPhail, 1963).

The Great Basin is typical range country; grazing is seasonal and extensive, and settlement is extremely sparse.

The creosote-brush zone

The creosote-brush zone, also known as the warm desert zone, is characterized by very low rainfall and very hot summers. In the south-west are the Mojave and Sonoran Deserts; eastward lies the Chihuahuan Desert.

The *Mojave Desert* occupies extreme southern Nevada, southeastern California, and a small part of northwestern Arizona. It is an upland desert, in the rain shadow of the southern Californian mountains. Precipitation is very low (35–130 mm annually) and occurs mainly in winter and early spring. Winters are mild, but summers are very hot (McKell, 1985).

The *Sonoran Desert* is the lowest, hottest, and most diverse of the North American

deserts. It occupies southeastern California, southern Arizona, and most of Baja California in Mexico. Rainfall is mainly biseasonal, with a tendency to summer rainfall to the southeast and winter precipitation to the north and west. Average annual precipitation ranges from almost nil to about 320 mm on the eastern range. Winters are mild and summers very hot. A frost-free growing period of not less than 300 days, permits the production of 'off-season' food crops in winter, under irrigation.

The Chihuahuan Desert is the second largest desert in North America. It is mostly a vast intermountain plateau that occupies a major part of the states Chihuahua, Coahuila, San Luis Potosi, and Nueva Leon in Mexico, and parts of western Texas and southern New Mexico in the United States. Average annual precipitation is between 60 to 250 mm, with great seasonal variability. Rainfall comes in small, intense storms in summer, winters are dry. Occasional frosts occur during the normally mild winters. Summers are very hot (McKell, 1985).

The Great Plains

The Great Plains extend from Canada to the United States–Mexico border. The Rocky Mountains form their western border.

The Great Plains are the climatic analogues of the Russian steppes, stretching in a belt from about 22° to 54°N, and thus reaching into Canada. They form the largest area of grassland of North America. Whilst winter temperatures vary widely, averaging from 10 to 20°C in the south to below 0°C in the north, the differences in summer temperature are far less marked. The amount of insolation and rainfall, and the relative humidity of the air, vary very little from south to north.

Average annual rainfall increases from 350 mm in the west to 500 mm in the east. Rainfall is of the continental pattern, most of it occurs in summer. High winds and the long hours of sunshine contribute to high evapotranspiration rates and reduce the effectiveness of precipitation, so that light rains are of little value. The winters are dry, with clear skies and the ground mostly frozen. Soil-water recharge is therefore confined mostly to the period in the autumn before freezing, and to early spring after thawing (Shaw, 1965). Crop production is precarious and the rural population very sparse.

The *Northern Great Plains* have a continental climate; the average mean temperature from April to September is 15°C, and the mean annual temperature is 5°C. Summer temperatures may reach 38°C, and winter temperatures of lower than –45°C have been recorded. Average rainfall ranges from 250 mm along the western border, to 500 mm on the eastern border. About two-thirds of the precipitation occurs in spring and summer, and about 20% is in the form of snow (Cannell and Dregne, 1983).

The *Central Great Plains* are primarily semi-arid (75% of the region) whilst 20% is considered subhumid, and only 5% is arid. Precipitation is erratic and may vary from half to double the long-term averages, which range from 300 to 800 mm. Up to 80%

of the precipitation occurs during the growing season, from April to October (Cannell and Dregne, 1983). Most of the cultivated area is in winter wheat; other crops grown on a significant scale are: sorghum, barley, millets, maize, oats rye and sunflower (Greb, 1983).

The *Southern Great Plains* have a rainfall that is erratic and ranges from 400 mm in the drier areas in eastern New Mexico to about 875 mm in the main wheat growing areas. Soils range from deep sands to clays. Because of low storage efficiencies (15–25%), soils are not often filled to capacity at crop planting, and subsequent yields are low unless precipitation is timely and adequate (Unger, 1983).

The Canadian prairies

On the northern fringe of the Great Plains is the Canadian dry belt, comprising southern Alberta and Saskatchewan, in which rainfall is still lower than normal for the general region, and falls to as low as 300 mm. This part of the region also has a higher degree of rainfall variability, a longer duration of droughts, and a higher ratio of evapotranspiration to precipitation than the general region (Trewartha, 1961).

Most of the rainfall falls during the period April, May and June. On the average, one-third of the precipitation is snow. The frost-free period ranges from about 80 days in the north to about 120 in the south. The climate is continental; winter temperatures may fall below -48°C , whilst summer temperatures often reach 38°C (Cannell and Dregne, 1983). Spring wheat is the major crop grown, followed by barley, oat, rapeseed and hay. Summer fallow accounts for nearly 40% of the cultivated area (De Jong and Steppuhn, 1983).

South America (Fig. 1.6)

The desert zone

The arid zone of South America forms a long narrow strip along the western coast between the sea and the Andes, reaching almost to the Equator (Fig. 1.6). Included is the Atacama Desert, in Peru and northern Chile, which is an almost rainless region considered by some to be the driest area on earth (McDonald, 1959). From northern Peru (approximately 5° to 6°S) to northern Chile (approximately 26°S) the highest average rainfall in this zone is under 50 mm, while in parts no rainfall has been recorded over periods of one or more decades. At best, effective rains occur at intervals of several years. The extreme aridity is surprising in that no part of this desert is far from a tropical ocean.

A unique feature of this arid region is that occasionally, once in several years, frequent torrential rains may occur during one or more summer months, so that, practically overnight the desert takes on the characteristics of an area of tropical wet climate. These heavy rains are extremely destructive, as they flood the irrigated valleys, destroying crops, roads, bridges, and even entire villages (Trewartha, 1961).

Despite its rainlessness, the coastal strip is extremely foggy, because of a cold ocean current that parallels the coastal desert.

This moisture stimulates the growth of a sometimes profuse vegetation.

The central part of the belt has a very low relative humidity, high luminosity, and very few cloudy days, resulting in an almost complete lack of vegetation.

Next to the Andes, precipitation increases; extra water comes from canyons, underground rivers, summer surface runoff, and other sources resulting in the creation of oases, transversal valleys of the desert, salt flats and pampas. Underground water is present at less than 20 m depth (Gasto et al., 1985).

The semi-arid areas

In the rain shadow of the Andes is a semi-arid region extending inland to the east; this includes the pampas plains of the Gran Chaco, with mild winters and moderate winter rainfall.

Much farther north, along the Colombian and Venezuelan coasts are located the *llanos*: the climate consists of a dry season followed by an extremely wet season, with most of the rainfall occurring in summer and autumn, and with relatively few rainy days. During the rainy season, the soil surface is covered in many places by water, which adversely affects growth (Gasto et al., 1985).

In northern Brazil there occurs an area of dry climate which is atypically situated, occupying an intermediate position between the winter-rainfall area to the east and the summer-rainfall area to the south. The area of drought varies considerably in extent and location from year to year; fairly extensive areas have under 600 mm of annual precipitation while there are restricted areas with less than 400 mm. The rains occur in the form of heavy showers extending over a small area at a time (Trewartha, 1961).

Moving inland from the rainy coast, the *caatingas*, an area of recurring droughts and often disastrous floods, is encountered. The soil is hard and sandy, and covered by drought-resistant scrubby brush (Bowden, 1979).

Mediterranean-type climate

In central Chile, the climate is typically Mediterranean, with a long summer drought followed by a short winter rainy season; in the north, annual rainfall amounts to 200–250 mm and increases towards the south up to 1400 mm (Gasto et al., 1985). Frosts are rare. During summer, temperatures are usually between 32 and 35°C (Di Castri and Mooney, 1973).

Australia

Dry climates occupy the entire mainland of the continent of Australia except in its northern, eastern, and part of its southern, margins (Fig. 1.7).

About 40% of Australia, or some 3.2 million km², consists of hot desert, with mild

to hot winters. This desert occurs not only in the region of the subtropical belts of the trade winds, but also in the rain shadow of the mountain ranges of the eastern coast.

Although the Australian desert is one of the most extensive in the world, precipitation in it is higher than in other low-latitude deserts. Thus the driest parts of the Australian desert average about 125 mm of rain annually (McDonald, 1959). Whilst in most other low-latitude deserts the annual rainfall increases inland, the opposite is true in Australia (Trewartha, 1961). The rains occur in the north mainly in summer, and in the south mainly in winter. Between these two regions lies a zone without a well-defined rainy season; the occasional precipitation can occur in any month of the year (Walter, 1962).

Groundwater is the major, and often the only, source of water in arid Australia; large reserves of groundwater occur in sedimentary basins. The Great Artesian Basin, e.g., supplies water for livestock and domestic use from about 20 000 bores over an area of 1.74 million km² (Williams and Lazarides, 1985).

There is, as yet, no evidence of erosion in the Australian desert or of its expansion. There is, however, widespread soil disturbance, following injudicious grazing use in the semi-arid ranges (*ibid.*).

Around the central desert core of Australia, with the exception of parts of the west and south coasts, is a fairly broad ring of semi-arid lands with erratic summer rainfall and tropical temperatures, which separates the desert from the humid climates on the margin of the continent. Grazing is practised in the more favourable areas of these semi-arid lands.

Causes of aridity

Rainfall generally occurs when the moisture-laden air rises, expands, and cools. As a result, vapour condenses and precipitation occurs.

The distribution of world rainfall is influenced by a great number of factors, of which the principal ones are: the characteristics of the general circulation of the atmosphere, relief, and the distribution of land and sea (Butzer, 1961).

General circulation of the atmosphere

The hydrological cycle

The earth's moisture is involved in a cycle of continuous circulation (Fig. 1.8) called the 'water cycle' or 'hydrological cycle'. Water is evaporated from the soil and from the water surfaces by solar energy, and transported as vapour by the general circulation of the atmosphere. Eventually the moist air is cooled to the point of condensation and may fall as precipitation.

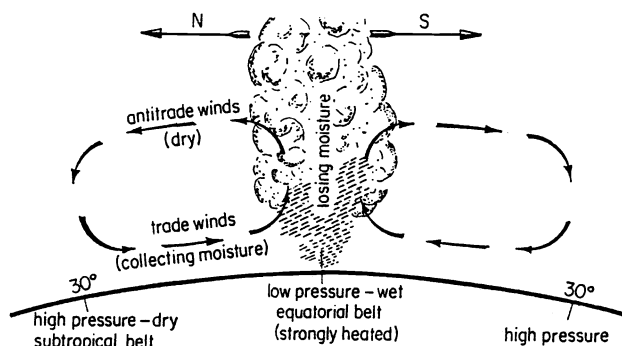


Fig. 1.8. Schematic presentation of the circulation pattern of the atmosphere between the Equator and 30°C latitude north and south.

Cause

The basic cause for the general circulation of the atmosphere is the unequal heating of the earth by the sun. The polar regions have an annual heat deficit, whilst the equatorial belt receives more heat from the sun than is lost by radiation into space. This temperature gradient between the equatorial belt and the polar caps provides the energy to set in movement a general circulation of the atmosphere, transporting heat from low to higher latitudes, and thereby mitigating the disparities in heat distribution over the earth.

Expressed in its most simple terms, the air heated over the equatorial belt would rise, flow polewards in the upper levels of the atmosphere while progressively losing heat by radiation, and then subside over the poles. The cooled air would then return to the Equator near the earth's surface.

This theoretical circulation pattern would be along the meridians of longitude, as its basic causes are the temperature gradient along the meridians. However, experience shows that there is not a mere single circulation system conforming to the above oversimplified pattern; instead there are mainly three systems, essentially zonal in character, that result in a consistent pattern of winds and precipitation the functioning of which is still not fully understood.

Zonal systems

(1) In the *equatorial region* there is a belt of relatively low and very uniform pressure, called the Doldrums.

(2) In the *subtropical latitudes* there is a broad belt of high uniform pressure. In the northern hemisphere this high-pressure belt lies approximately between latitudes 25° and 35°N, and is confined mainly to the oceans. In the southern hemisphere, the belt is approximately along the 30°S latitude, and encircles the entire globe (Hare, 1961).

(3) In the vicinity of the *Arctic and Antarctic Circles*, there are belts of low pressure.

Relatively high pressure occurs at the *two geographical poles*.

Main circulation systems

The combined effect of the meridional temperature gradient, the earth's rotation, and the pressure belts, results in three main circulation systems of the earth's atmosphere.

Equatorial low-pressure belt. The trough of low pressure in the equatorial belt causes surface air to move in from the subtropical high-pressure belts. As this air flows over warm oceans and tropical jungles which evaporate huge quantities of water, it becomes moisture-laden. The heated land mass of the equatorial region in turn heats the damp surface air, which expands and therefore becomes lighter and rises. As the heated air rises it continues to expand, thereby using up some of its energy and becoming progressively cooler. When the air has been cooled to below dew point, cloud formation occurs. Continued cooling then causes precipitation, resulting in heavy rainfall in the afternoon or evening. This occurs practically all the year around, and is typical for the equatorial belt.

Subtropical high-pressure belts. The air that has ascended from the equatorial belt, after losing much of its moisture, flows poleward north and south in the upper regions of the atmosphere. By the time it is above latitude 30°N or S, the airstream is deflected by the earth's rotation. This causes an accumulation of air above these latitudes (called the Horse Latitudes) and produces belts of high pressure on the earth's surface.

Those parts of the airstream that have lost their heat descend slowly over the high-pressure subtropical belts. The slowly descending air is so dry that there is no condensation, the sky remains clear, and practically no rainfall occurs. Thus large arid and semi-arid zones are created in these latitudes. In winter, storms from the higher latitudes occur occasionally, resulting in moderate winter rainfall.

In addition to air circulation in the upper atmosphere, surface winds are also involved in determining the rainfall régime of the dry region. Because of the subtropical high-pressure, surface winds blow out of the subtropical highs to the equatorial low, moving in to replace the air that has ascended aloft at the Equator in the manner described above. These surface winds, instead of being northerly and southerly in the northern and southern hemispheres, respectively, are deflected by the earth's rotation – to the right in the northern hemisphere and to the left in the southern hemisphere, thereby becoming north-east and south-east winds. They are called the 'trade winds' or, simply '*trades*'.

These winds are steady and moderate, carrying moisture away from the subtropical belt. As the air moves from the subtropical belt towards the Equator, its temperature rises and its relative humidity remains low. The skies are clear, the weather is warm, and only light rainfall occurs. Wherever mountain ranges force the trade winds to rise, rainfall occurs on the windward side, whilst the leeside remains arid. As

the trades approach the Equator they become progressively more humid and unstable; however, they do not actually reach the Equator, but rise at some distance from it. As a result, a narrow low-pressure belt is formed between the two belts of trade winds – the so-called doldrum or equatorial calms, in which the air is generally calm or the winds are very light.

The general circulation of the atmosphere, involving the equatorial low-pressure belt and the subtropical high-pressure belts, explains why, on a worldwide scale, the major arid and semi-arid regions are generally found in the zones between latitudes 20° and 30° in each hemisphere – in particular in the western parts of the continents, where upper-level subsidence is particularly strong. The aridity even affects rainfall over the oceans in these latitudes, proving that a process effectively preventing precipitation is involved.

In these zones are found the great tropical and subtropical deserts. The eastern sides of the continents are the windward sides; they are under the influence of maritime air currents and so their air masses are relatively warm and humid, causing relatively abundant rainfall. These regions may therefore be considered as a poleward extension of the rainy tropics (Trewartha, 1954).

The Polar Circle low-pressure belts. Air moves polewards from the subtropical high-pressure belts to the subpolar lows mainly at the surface. As a result of deflection by the earth's rotation, the winds develop into the so-called 'mid-latitude westerlies' or, simply, '*westerlies*'. These are neither constant nor steady in direction, as they are affected by various secondary circulation factors. The regions of prevailing westerlies lie between 35° and 60° in each hemisphere, and comprise the cool, humid climates of the earth.

Briefly it can be said that the circulation systems of the atmosphere, which tend to be zonal in character, are the basic determinant of world climates. These climates accordingly tend to occur in latitudinal zones, as was already observed by ancient civilizations.

Relief

Orographic rain

When rising ground, or mountains running at right angles to the prevailing winds, deflect moisture-laden air upwards, the air cools, resulting in condensation and subsequent precipitation. This is called 'orographic' rain (Fig. 1.9). When the air moves down the leeward side of the mountain range, it has already lost most of its moisture. During subsidence, the air again becomes warmer and its relative humidity is decreased further, which explains why the leeward side of a mountain has little rainfall. Examples of this so-called rain-shadow effect are the Patagonian Desert, which lies in the rain shadow of the Andes, and much of the Australian Desert behind the

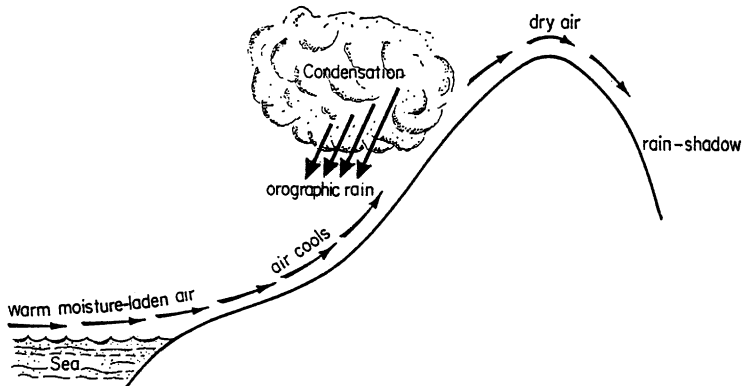


Fig. 1.9. Effect of relief on rainfall: orographic rain.

Queensland coast, which is situated in the rain shadow of the mountains that lie across the path of southeasterly winds.

Even if the mountain barrier does not completely block the passage of moisture-laden air, reduction in precipitation to the lee of the mountain range may be substantial and amount to 60–70% of its rainfall potential. Dryness can be increased by subsidence of air from near the inversion down the lee slopes of the range. For this reason, mountain-enclosed inland basins, such as Death Valley (USA), e.g., are often extremely dry (Lockwood, 1976).

High plateaux also tend to be dry, because here the air has lost most of its moisture before reaching these high altitudes.

Distribution of land and sea

Winds may also arise as a result of the seasonal heating and cooling of the continents, which warm up rapidly in summer and cool rapidly in winter. Such winds are the so-called '*monsoons*', which in summer are moist and blow landwards whereas in winter the direction is reversed. This latter outflow of dry air is characterized by lack of precipitation.

The greater part of the earth is covered by oceans; the distribution of land and sea will, therefore, have a marked effect on climatic patterns only in regions in which large land masses are involved – such as Asia and, to a lesser degree, Africa, the Americas, and Australia – and in which the zonal circulation pattern may be entirely obscured by the great thermal differences between land and sea.

Air moving over warm oceans becomes moisture-laden. When it moves inland, any factor that causes this air to ascend, such as rising ground or a wedge-shaped mass of cold air, will result in cooling, condensation, and precipitation (Fig. 1.10). Land areas near warm ocean waters are characterized by high temperatures, high air humidity,

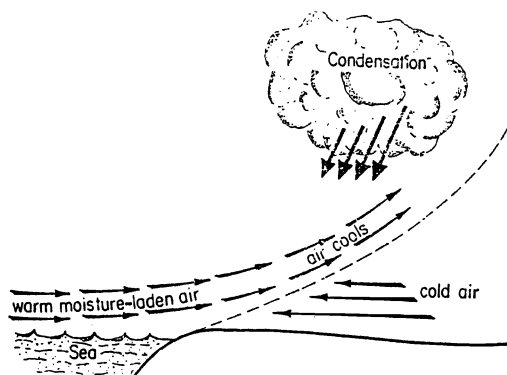


Fig. 1.10. Effect of warm moisture-laden air encountering a cold air front.

and heavy rainfall. However, the moisture-laden winds progressively lose most of their moisture whilst passing over the land mass, so that the continental interiors, far removed from the warm oceans, are generally dry. The Gobi Desert is an example of aridity due to sheer distance from oceanic moisture. A characteristic of the continental arid regions is that precipitation may occur at all seasons, with a tendency for there to be more rainfall in the summer than in the winter. In winter, the low temperatures reduce the water-vapour capacity of the air, whilst in summer there is an indraft of warm, humid air from the oceans, with the surface heating of the air causing convective activity which occasionally results in precipitation.

However, coastal areas may also be arid if they border on oceans with cold currents flowing parallel to the coast – especially if the normal temperatures of the region are high. This is a regular characteristic of the tropical and subtropical west coasts along which currents, which have originated over the poles, flow towards the Equator. Warm air moving landwards from far out in the ocean is cooled when it moves over the cold water of the ocean near the shores; as a result of the drop in temperature, heavy fog may be formed. As the air which has lost much of its humidity moves inland, it is warmed by the land surface, and its relative humidity is also lowered. Coastal regions with cold water along their shores are therefore arid or semi-arid, notwithstanding the frequent morning fogs near the coast. The deserts of Chile, Peru, and Southwest Africa, are typical examples of aridity caused by cold oceanic currents.

From time to time, the warm equatorial counter current, El Niño, spreads east and south, displacing the cold Humboldt current; air moving inshore is no longer chilled and stabilized in its lower layers and heavy rains result in the normally extremely arid coastal region (Grove, 1980).

Summary

Of all the factors which lead to aridity, the two most important (McDonald, 1959) are the low frequency of occurrence of an adiabatic rise of large bodies of air, and the remoteness from an oceanic moisture source in the prevailing wind direction. The principal arid regions of the world occur where one or both of these factors operate:

(1) In the flat trade-wind deserts of Africa (Sahara), Arabia, and Australia. The primary reason for the aridity of these regions is the chronic lack of lifting processes. This is indicated by the fact that within these regions are isolated 'humid islands' –e.g. isolated mountains, such as the Atlas of North Africa, which, by causing orographic lifting, have more precipitation than the surrounding plains (McDonald, 1959).

The reasons for the scarcity of dynamic lifting processes in these low-latitude arid regions are:

- (a) They are too far equatorward to be strongly influenced by the extratropical wave cyclones that increase precipitation in the regions lying polewards of the deserts.
- (b) On the other hand, they are too far poleward to benefit from the summer poleward movements of the humid equatorial air.
- (c) They are also too far westward in their land masses to be affected by the hurricane activity of low-latitude east-coast littorals.

(2) In the interior of continents, especially in areas enclosed within mountain barriers (Mongolia, southwestern Siberia, the Great Plains of the USA).

(3) On the tropical and subtropical west coasts of continents (Peru, northern Chile).

(4) On leeward mountain slopes (Patagonia, Australian desert).

(5) On high plateaux (Tibet).

The reason for aridity in these regions is the remoteness from an oceanic moisture source. This remoteness may be due either simply to distance, or to the so-called 'hydrometeorological remoteness' caused by mountain barriers that block the inflow of moisture-bearing winds (rain-shadow deserts) (McDonald, 1959).

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CHAPTER 2

Climatic Factors and their Effect on Crop Production

Introduction

Climatic factors influence all aspects and stages of plant growth and hence affect agricultural productivity and stability of production. Their influence extends from the upper reaches of the atmosphere, in which spores and pollen are encountered, to the soil depth penetrated by the roots. Although water supply plays a dominant role in dryland agriculture, other climatic factors either enhance or reduce problems of water deficit, or have beneficial or negative effects on crop production.

Enormous amounts of climatic data are collected daily, in practically every country. These efforts involve considerable investment in personnel and capital; it would be an exercise in futility if these data were not put to use for increasing agricultural productivity.

Agricultural meteorology has been defined as the discipline that studies the relationship between agricultural production and climatic factors and attempts to enhance their favourable effects and/or attenuate their adverse effects.

Much information has accrued in this discipline in recent years as the result of a considerable research effort in the laboratory, in growth chambers and in the field, and practical application of this know-how is being developed.

Plant responses to climate

Each climate factor has a range of optimum intensity which differs with species, and within species, with different growth stages.

Beyond the limits of the optimum intensity, plant development is adversely affected, either by excess or deficiency intensity of the factor involved. The resulting stress may cause physical or chemical changes, such as structural damage or destruction of enzymes that are vital to essential metabolic processes, or they may simply cause a slowing down of these functions, that return to normal when the stress ceases.

According to the degree of intensity, the effects of a climate factor may therefore be favourable, neutral, harmful or lethal.

Different species, varieties within species, and even individual plants have developed different response mechanisms to stress resulting from excessive or deficient intensity of climatic factors:

- *avoidance*, whereby growth stops or is concluded under climatic stress;
- *adaptation*, whereby the plant continues to function under the stress;
- *tolerance*, whereby the plant survives the stress.

These generalized forms of response will be treated in more detail in Ch. 6.

Precipitation

Rainfall

The distinctive trait of the arid lands is, of course, insufficient precipitation. In the deserts the average amount of rainfall is never great, though heavy showers may occur occasionally. The mean annual precipitation totals at a few typical desert locations are: Yuma, 76 mm; Baghdad, 175 mm; Khartoum, 150 mm. In most parts of the Egyptian Desert, the annual rainfall does not exceed 10 mm, while in parts of the Libyan Desert several years may pass without any rainfall whatsoever (Migahid, 1962). Precipitation in some desert areas is sometimes too small to be measurable.

Rainfall patterns

Dregne (1982) describes four patterns of rainfall in dry regions:

Winter rainfall is the characteristic of Mediterranean climates (cf. p. 12); because it occurs in the cool season, rainfall is very effective. Annual precipitation varies from 250 to 500 mm, with the largest monthly variation at the beginning and end of the rainy season. Rainfall intensities are relatively low.

Summer rainfall is generally the result of monsoon activity (cf. p. 34) during the warm summer months; the cool period is dry. The length of the rainy season increases as one approaches the Equator.

Continental rainfall is characteristic for inland areas of continents, and is typically found in central North America, central China, the former Soviet Union, and Argentina. Rain typically occurs in localized, intense storms. Destructive hailstorms are a frequent occurrence. Rainfall is mainly in summer, but some precipitation may occur in every month.

Multimodal distribution is confined to certain areas in Africa and South America located near the Equator. There are two alternating rainy and dry seasons. The intensity and duration of the rainy seasons vary considerably from year to year and the two dry seasons are not of equal length. The storms tend to be more intense than in the summer pattern, but less than in the continental pattern.

Effectiveness of rainfall

Average annual amounts of rainfall are not an accurate measure of its effects on the moisture regime in general, and of the amounts of water available to crop production in particular. In Ch. 1, an example was given of two regions that have almost identical average annual rainfall and yet the one has a typical semi-arid climate with a completely dry season of six to seven months, whilst the other has a humid climate practically throughout the year (Fig. 1.2).

Intensity and frequency. It is commonly stated that the distribution of rainfall throughout the growing season is more important than the total amount. This statement implies that a greater number of relatively light rains, equally spread over the rainy season, is preferable to a small number of relatively heavy rains. This assumption, notwithstanding its apparent logic, is not correct.

Evaporation causes the rapid loss of water from a moist soil surface; as a result, the upper soil layer, to a depth of 10–12 cm dries out very rapidly after a rain. This means, in practice, that rainfall that is insufficient to wet the soil beyond the 10–12 cm layer, will generally be of little use to crops.

Effective rainfall is the minimum amount of rainfall, occurring on a single occasion, that ensures some water storage under favourable soil conditions. The amount needed for this has been estimated as 15–20 mm for a single rainfall. The annual effective rainfall commonly amounts to about 30% of the total rainfall (Bagnold, 1954).

Loss of water by evaporation from the soil surface is greatest from a bare soil and becomes progressively less as the plant cover increases. However, a significant proportion of rainfall is intercepted by plant canopies, and never reaches the soil. The proportion of water lost by canopy interception is particularly great when rains are light and of low intensity.

Plants with relatively erect leaves, like maize, e.g., may allow intercepted rain to move down the plant rapidly, and be absorbed by the soil around the stem. This allows water from even relatively light showers to be saved from evaporation. Removal of water from depths below 10–12 cm is almost entirely due to extraction by the roots of the plant, and does not contribute to water losses.

Infiltration and run-off. A characteristic of rainfall in the dry regions is that rain frequently comes in a few heavy showers of short duration, which engender considerable run-off. It is not uncommon for 50% of the annual precipitation to occur on 10–15% of the rainy days (White, 1966). Without adequate conservation management, not only is a considerable proportion of the rain lost through run-off, but considerable loss of soil may occur through erosion.

The effectiveness of rainfall depends on the rate of infiltration into the soil, which in turn reduces losses by evaporation. The capacity of a soil to absorb and store water, depends on its texture and structure, depth, moisture status, and slope. The

presence of impervious layers, and the nature of the subsoil also affect soil-water storage capacity.

Examples of rates of infiltration for different soil types are presented in Table 2.1.

The effectiveness of light falls of rain depends on soil texture: 10 mm of rain may penetrate rapidly and deeply into a sandy soil and so be protected against evaporation; whilst the same amount of rain may penetrate only to a depth of 2 cm into a clay soil whose surface was air-dry, unless the interception of the rain by the leaves and its channelling to the stems results in localized deep penetration (Passioura, 1983).

Sandy soils may have a limited water-holding capacity if an impervious layer is present at a relatively shallow depth, whilst a similar layer, just beyond the root zone, will be favourable for water retention in such soils.

Heavy soils, when dry and cracked, have a very high initial infiltration rate, which declines rapidly as the soil surface is compacted by the rain and the cracks are filled.

Slope has a considerable influence on the ratio between infiltration and run-off. It also influences the velocity of run-off and hence the degree of soil erosion. Most soil conservation practices aim at reducing this velocity by reducing the slope at which the run-off is removed.

From the foregoing it is possible to conclude that effectiveness of rainfall is influenced by a variety of interrelated factors, often with conflicting results:

(1) Very light rains (less than 10 mm) generally contribute, directly, little or not at all to stored soil moisture. They can, however, be beneficial by reducing temperature, increasing air humidity and thereby reducing the water requirements of the crop.

(2) Much of the water produced by high-intensity rains is lost through run-off.

(3) Rains of medium intensity, but of sufficient duration to produce more than 10 mm, are the most efficient in their contribution to water stored in the root zone. However, an excess of precipitation beyond the field capacity of the root zone (not an uncommon occurrence in the seasonally dry zones), leads to losses of water by drainage.

Timing. Short-term, intermittent drought periods, especially during the stages of

TABLE 2.1
Infiltration rates for different soils

Soil type	Infiltration rate (mm/hour)
Deep sand, deep loess	7.6–11.4
Shallow loess, sandy loam	3.8– 7.6
Clay, poor in organic matter	1.3– 3.8
Saline	> 1.3

Source: Passioura (1983).

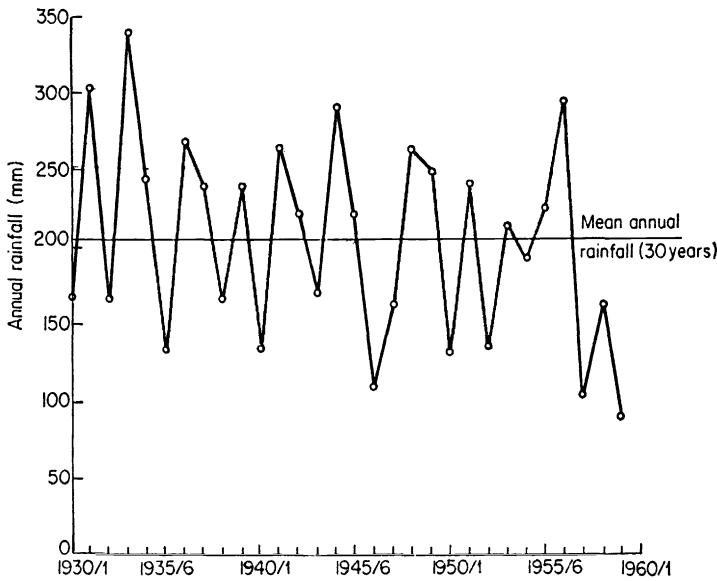


Fig. 2.1. Seasonal variability of rainfall in a dry region (Bersheeba, Israel).

grain growth when plants are most susceptible to stress, can cause dramatic reductions in yield, even in years with relatively satisfactory total amounts of rainfall (cf. p. 203).

Bowden (1979) writes: "The random pattern of precipitation has on numerous occasions been responsible for bumper crops in years when the annual rainfall was less than 250 mm. In these instances, the small amount of moisture fell during periods of greatest need. In contrast, there is little assurance of good production in those years of greater-than-average precipitation if it comes at the wrong time of the year".

Duration of rainy season. In all semi-arid areas, the duration of the crop growing season is limited by the duration of the rainy season. For example, in the Sahel three bioclimatic zones based on the length of the rainy period/crop growing season are recognized: the southern zone (75 to 90 days); the Sudan zone (165 days); the northern Guinean zone (165 to 210 days) (Kanemasu et al., 1990).

Dependability of rainfall. Variability of rainfall is the greatest hazard to rainfed crop production in the semi-arid regions, in particular in the fringe areas bordering on the arid regions. The impact of the considerable variability of rainfall is enhanced by high evaporation rates, which further increase as rainfall diminishes (Grove, 1985).

It is a general rule that the drier the climate, the less reliable is the rainfall (Köppen and Long, 1958). With mean annual rainfalls of 200 to 300 mm, the amount recorded

in a given year varies from 100 to 500 mm; with a mean annual rainfall of 100 mm, the range is 30 to 350 mm. Coastal desert environments present extreme examples of rainfall variability as exemplified in Peru; in most years little or no rain falls, but changes in ocean currents cause heavy rains and flooding (Grove, 1985).

The dry regions are therefore characterized by the considerable variety in annual amounts of rainfall and its distribution in time (Fig. 2.1). Because of this great variety, the dividing lines between arid, semi-arid, and subhumid shift considerably from year to year.

Wallen (1968) has shown that the minimum annual rainfall at which rainfed crop production is possible in the Middle East varies from region to region, mainly because of differences in variability. He calculated that the amount was as low as 180 mm in areas of relatively regular rainfall in Jordan and southwestern Syria, and as high as 230 mm in the agricultural region of northern Iran. The overall value for the limit to rainfed farming in the Middle East was found to be 240 mm annual rainfall, with a variability of 37%.

Additional examples of variations in precipitation and grain yields are provided by data from three experiment stations in Oregon (see Table 2.2).

A 45-year study of the effects of rainfall variability on crop yield in central Washington, a dryland region of the US, found that for a wheat–fallow rotation, the standard deviation of yield was 692 kg/ha, for an average yield of 1593 kg/ha (Dryland Agriculture Technical Committee, 1979).

A study of long-term weather records in Africa and India has shown that the

TABLE 2.2
Variations in precipitation and grain yields at three locations in Oregon

	Precipitation (mm)	Grain yields (kg/ha)	
		traditional variety	improved variety
(a) Pendleton (Columbia Basin Agricultural Research Center)			
Maximum	555	3982	6154
46-year average	405	2852	3592
Minimum	268	1715	1601
(b) Moro (Sherman Experiment Station)			
Maximum	440	3518	3841
65-year average	290	1809	2058
Minimum	154	666	619
(c) Lind, Washington (Dryland Research Unit)			
Maximum	574	3350	3733
55-year average	241	1594	1762
Minimum	122	276	269

Source: adapted from Dryland Agriculture Technical Committee (1979).

coefficient of variation of annual rainfall varied from 9 to 45%, and the largest variations occurred in the areas with lowest rainfall (El-Swaify et al., 1984).

High-rainfall years raise the long-term mean more than low-rainfall years lower it. Therefore, there are more years below the mean than above the mean; the lower the rainfall, the greater the degree of skewness (Steiner et al., 1988).

Variability of rainfall is therefore the greatest hazard to rainfed crop production. In above-average rainfall seasons, cultivators are tempted to till and sow large areas on the fringe of a semi-arid area; then, in the following below-average seasons, which are usually accompanied by higher-than-average temperatures, disastrous crop failures may result.

For example, in Montana, rainfall was ample for crop production during the period from 1909 to 1916; a boom in wheat production ensued, during which wheat yielded up to 1.68 ton/ha. A succession of drought years followed from 1919 to 1925 and wheat failed. High winds and dust storms exacerbated the situation. During that period, one out of two farmers lost their land (Jones and Brown, 1987).

In a study covering a period of 68 years, from 1878 to 1946, on the effect of rainfall variability on the prosperity of agriculture in eastern Montana, the picture reflected by Table 2.3 emerged (Lomasson, 1947):

The probability of obtaining a bumper crop in this 'wheat region' is not more than one year out of twenty-three whilst complete crop failures, as a result of drought, can be expected in one year out of seven.

Because of the considerable variability of rainfall, it is difficult for the farmer to make decisions on the choice of crops and cultivars, the time to plant, the rates and kinds of fertilizers to apply, and other management practices. Consequently, "managing dryland agriculture is, in reality, adopting procedures to cope with a dry, variable climate, including dealing with the economic risks of possible crop failure one year and bumper harvests the next" (Steiner et al., 1988). The authors conclude that it is imperative to emphasize probabilistic analysis and rely less on mean values in the use of climatic parameters. One example of such an approach, aptly named 'response farming' by Stewart (1986, 1987) is to base managerial decisions on whether the onset of the rainy period is early or late. Recent studies have shown that

TABLE 2.3

Rainfall variability in eastern Montana

	No. of years	Percentage of total no. of years
Abundant rainfall (double the average)	3	4.4
Average or above-average rainfall	31	45.5
Dry years, below average	24	35.3
'Killer' years, with extreme droughts	10	14.8

seasonal rainfall increases predictably with an early onset of the rainy period (Steiner et al., 1988). This generalization has been confirmed for winter rainfall areas (North Africa, Near East) (Stewart, 1986); as well as summer rainfall areas (India, the Sahel) (Stewart, 1987).

Climatic records of more than 20 years are available in most areas, and can be used to calculate rainfall probability levels (Stewart, 1987).

Kanemasu et al. (1990) have also attempted to predict the essential characteristics of the approaching monsoon season. On the basis of long-term analysis of climate data, these authors found a strong, highly significant relationship between rainfall season duration and date of onset of the rains. An early onset of the rains means a longer growing period and a higher total amount of rainfall, whereas a delayed onset of the rainy season results in a shorter growing season, and less-than-average rainfall. In most instances, it was found that the duration of the rainy season correlated much better with the time of onset, than rainfall amount.

Rainfall cycles

There is a tendency for wet and dry years to cluster together, and many efforts have been made to define periodicities in the climatic record that might allow extrapolation into the future. Atmospheric modeling, which involves accumulating and processing climatic data, partly derived from satellite monitoring, may have more predictive value (Grove, 1985).

Cycles of periods of low rainfall alternating with periods of higher rainfall, as symbolized by Pharaoh's dream of seven fat calves followed by seven lean calves, are a common occurrence in dry zones.

Persistent droughts during successive years can lead to desertification through the destruction of natural vegetation by overgrazing; a succession of favourable rainfall years may lead to arable cropping in borderline regions, with disastrous results when the favourable cycle comes to an end, and the unprotected soil is blown away (cf. p. 45).

Steiner et al. (1988) conclude that: "Future emphasis will move toward flexible cropping systems where cropping decisions are based on the availability of stored soil water at certain times and on the probability of growing season rainfall. Computers will become an increasingly important tool in planning and managing successful dryland systems".

Rainfall and yields

Notwithstanding the major influence of rainfall on yield levels, yields are not always directly proportional to the amount of precipitation. Generally, yield levels are determined by the amount of precipitation above the basic minimum required to enable the crop to achieve maturity. If, e.g., under given circumstances 250 mm is the necessary minimum precipitation for a grain crop, 225 mm, or a reduction of only 25 mm,

may result in complete crop failure. Conversely, 50 mm above the minimum requirement may double the yields.

An example of this general rule is the yields of winter wheat, obtained on the loessial soils of Shaanxi Province in China, in which an increase of precipitation of one-third can result in a fivefold increase in wheat yield (Peiyuan and Ying, 1988).

Rainfall may also be in excess of the optimum and thereby cause reduced yields. This may sound paradoxical in relation to semi-arid climates. However, it will be remembered that the total rainfall in a semi-arid region may equal that characterizing a humid climate and yet be concentrated in a very short period. When this rainfall is concentrated in four to five months of the year, there may easily be periods when the rate of precipitation exceeds the capacity of the soil to absorb the rainfall. As a result, considerable run-off occurs from the waterlogged soil, plant nutrients are leached out of the rootzone, and crops are adversely affected by anaerobic conditions – especially if the excess precipitation occurs during the cool season.

Excess moisture after sowing may reduce germination; heavy rainfall during earing may cause lodging and impair pollination.

Rainfall productivity. Rainfall productivity (RP) has been defined as the agricultural production (in kg/ha or the monetary equivalent) in relation to the seasonal precipitation (in mm) (Krantz, 1981); it is the product of effectively used rainfall and water-use efficiency. From this definition it is clear that all the factors that influence water-use efficiency (cf. Ch. 5), in addition to effective rainfall, are involved in determining RP.

For example, research at ICRISAT on rainfall productivity has shown (see Table 2.4) that there are wide differences in this respect between different farming systems (Kampen and Krishna, 1978).

Even a relatively small amount of water stored in the soil, prior to sowing the crop, is important in dryland farming. This is the main justification for maintaining a period of fallow – even if this method is not very efficient in storing water (cf. Ch. 16).

For crops that grow under optimal moisture conditions, the yield potential is no

TABLE 2.4

Rainfall productivity of different farming systems

Farming system	Rainfall productivity	
	monetary value/ha	% of traditional
Traditional: single post-rainy season crop on stored soil moisture (deep vertisol)	Rs 12	100
Double-cropped vertisols, graded ridges	58	483
Double-cropped alfisol on broadbeds	130	1083

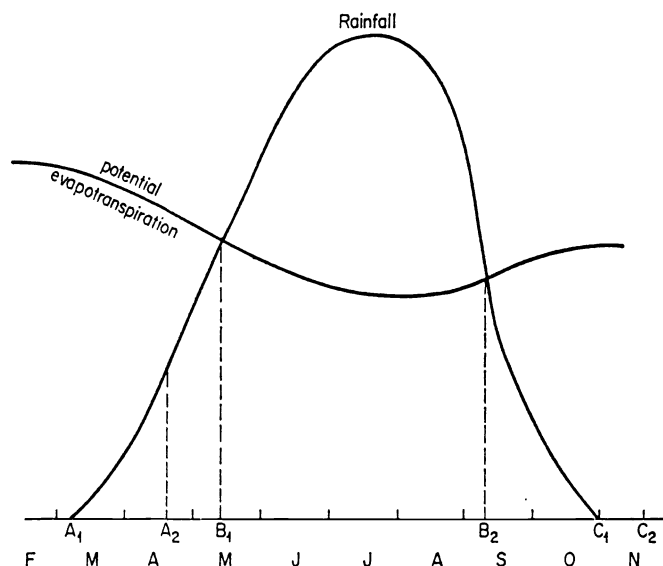


Fig. 2.2. Subdivisions of the cropping season in a semi-arid climate. A1: beginning of rainy season; A2: beginning of transition period (precipitation = half of PET); B1: beginning of humid period; B2: end of humid period; C1: end of rainy season; C2: exhaustion of moisture reserves in the soil. From Cochemé and Franquin (1967). By permission of the World Meteorological Organization.

longer determined by water, but by other factors, such as soil fertility, management practices, freedom from diseases, etc.

The low crop yields usually obtained in the semi-arid areas are generally attributed to the deficient moisture supply. Experience in many countries has shown that the yield potential can be considerably increased even under conditions of limited precipitation by cultural practices that conserve moisture, effective weed control, improved soil fertility, and improved varieties.

Humid and dry seasons in rainfed agriculture

The humid season of the semi-arid regions can be subdivided into three principal periods (Cochemé and Franquin, 1967; Bunting and Kassam, 1988) (Fig. 2.2).

The pre-humid period. The pre-humid period begins with the first rains (called 'Hay-ore' in the Bible), which signal the end of the dry season (point A1 in Fig. 2.2) and ends when precipitation equals potential evaporation (point B1). During this period, the rains fall on a dry profile from which all available water has been removed by a crop or by natural vegetation during the dry season (excepting where fallow has been effective in conserving water).

In the semi-arid tropics (SAT), the pre-humid period, also called the period of

short rains, may extend for one to two months (Kanemasu et al., 1990). This period is normally the time for sowing, which may be in dry soil if it precedes the first effective rainfall, or in moist soil if unusually heavy rains occur. Sowing in dry soil of course involves the risk that rainfall, while sufficient to cause germination, may fail to provide sufficient moisture for emergence and continued growth.

The reliability of rainfall at the beginning of the season is generally low; the first rains may be light or heavy, and are often followed by a rainless period of varying length. Hence, there is a high degree of risk in establishing a crop, as soil-water reserves are practically nil at this period (unless fallow is practised).

Only crops that can effectively withstand a number of periods of dessication between the beginning of germination and full emergence – such as wheat, barley and pennisetum – can be sown under these conditions. The risk involved in sowing in dry soil is considered to be justified by the possibility of increased yields, due to the likelihood of a longer growing season and more effective use of precipitation early in the season.

Where the risk of sowing in dry soil is too great, or in regions in which the soil is too dry and hard for tillage with primitive equipment, there is no choice but to wait for the early rains to soften the soil and ensure germination.

The tillage operations in this case become easier as one approaches point B_1 ; but once this point is passed, they become increasingly difficult and even impossible in heavy soils, as the soils become too wet for effective tillage.

At point A_2 on the graph (Fig. 2.2), precipitation equals one-third to one-half of potential evapotranspiration (depending on albedo). This is the normal mean evaporation rate of a bare soil (or one with a sparse vegetative cover) which is only occasionally moistened by rainfall. In principle, this is the time when germination and emergence become possible, and from this period onwards real evapotranspiration will increase exponentially, together with leaf area, until the crop shades the soil entirely. Ideally, this should coincide with point B_1 on the graph.

The humid period. This is the period during which total precipitation is usually in excess of PET, and therefore potential and real ET are equal. In SAT, this is the period of monsoons, also called the period of long rains (Kanemasu et al., 1990).

As the rains become established and the rate of precipitation exceeds ET, a wetting front begins to move down the profile at a rate determined by the balance between precipitation and water uptake by the crop. The wetting front carries with it soluble nutrients. If rainfall is sparse, and water penetration shallow, deep root penetration is not possible. Laterally spreading roots may help the plants to survive dry periods, if these are not too long, until the wetting front penetrates deeper layers.

The 'humid' period does not coincide with the rainy season: it begins later and ends earlier. During the humid period, the excess of precipitation over real evapotranspiration, provided it is not lost as run-off, is stored in the soil. If precipitation is sufficient, the entire rootzone is saturated to field capacity, and excellent moisture

conditions for crop production and especially for crop maturation during the post-humid period will prevail. Excess precipitation will either cause run-off or drain beyond the rootzone, or both.

If excess water does not escape from the root zone with sufficient rapidity to lower ground and into water courses, the profile may become waterlogged, excess water may run off the surface causing scouring and erosion, and low-lying parts of the fields may be flooded.

Other undesirable consequences of excess water during this period are leaching of nutrients beyond the root zone, anaerobic losses of N and damage to the roots.

The relative positions of B_2 on the graph (Fig. 2.2), and the dates of flowering (or earing for cereals), have a considerable impact on potential yield levels. The longer the humid period, and the later it ends, the greater will be the prospects for the maturation under favourable conditions of a larger number of fruits per unit area. However, the greater the coincidence of flowering period and peak moisture supply, the greater will be the danger of epidemic diseases.

In the *post-humid period* the total precipitation is inferior to potential evapotranspiration.

At the end of the rainy period, real evapotranspiration continues until the reserves of water in the soil formed during the humid period are exhausted.

Crop production may also be possible during the completely dry period, provided the land remains fallow during the humid season, and precipitation has been sufficient to fill the soil reservoir to the depth of the root zone. Adapted crops can then be sown during the dry season, and even produce high yields without receiving a drop of rainwater throughout their growing period.

Other sources of moisture supply

Snow

About one-fifth to one-third of precipitation in the dry middle-latitude regions falls as snow. A considerable proportion of this snow is blown off the fields and concentrates in ditches, gullies and along fences. Appropriate measures to reduce these losses could make an important contribution to soil moisture (cf. p. 124).

An important source of water supply to many arid regions is snowfall in the mountains bordering or within these regions. As snow melts in the higher altitudes, it provides a sustained stream flow that may continue into the summer, and is a valuable source of recharge of the aquifers. However, for this important water resource to be fully beneficial, effective flood control measures are essential.

Dew

Dew condensation. When surfaces, such as those of leaves or stones, lose heat rapidly by radiation, the air in contact with these surfaces is also cooled. When the

temperature of the air falls below a critical point called the 'dew point', dew condenses on the cold surfaces.

The immediate source of dew is the condensation of water vapour from the atmosphere. This vapour is replaced from the free atmosphere (dew fall) and from the soil (distillation), providing a moisture supply for continuous condensation throughout the night. If absorbed, dew fall is a real addition of moisture to the plant; distillation merely transfers available moisture from the soil to the atmosphere.

The formation of dew occurs mainly at night because it depends on radiational cooling of leaf and soil surfaces until they reach dew-point temperatures. According to Slatyer (1967), the main factors contributing to dew formation are:

- (a) a clear sky – cloudiness reduces radiation from the earth and plants;
- (b) low wind speed – otherwise turbulent mixing in the lower atmosphere will prevent the temperature from falling;
- (c) high air-humidity – so that the dew point is reached with relatively little cooling; and
- (d) vegetation of low heat capacity – open-branched and with leaf spread over a considerable height, so as to facilitate radiation loss.

Dew fall. When the leaf temperature drops below the dew point of the surrounding air, a water vapour transport from the air results, and water is condensed on the leaves, adding to the amount of water available to the crop. The total amount of dew is unlikely to exceed 1 mm nightly (Slatyer, 1967).

Dew rise. If the absolute humidity of the air is lower than that of the soil, a common occurrence in irrigated fields, vapour diffuses from the soil into the lower air layers. This process occurs in daytime but can continue into the night. If radiative cooling lowers the leaf temperature below dew point, water vapour can condense as dew. This distillation of water from the soil does not increase the amount of water available to the crop, and is therefore, generally of no benefit.

Though the amounts of dew rise may be as much as ten times higher than dew fall, it has little or no agricultural significance. Some desert plants may possibly benefit when it occurs in soils that are drier than the wilting point.

The only aspect in which there is no essential difference between dew fall and dew rise is in their effect on plant disease (EUROCONSULT, 1989).

Effects of dew on plant growth. Dew absorption has been found to vary widely with plant species; it is largely dependent on the intensity and duration of dew fall as well as on the soil moisture régime, being higher under dryland conditions than under irrigation (Waisel, 1958).

Dew can only provide a very small proportion of the water requirements of a normally transpiring plant, but may be of some importance to plants under water



Fig. 2.3. 'Teleilat el Einab' (the so-called dew mounds), built by the Nabateans in the Negev Desert (end Third Century, B.C.). Photo N. Tadmor.

stress. Occurring as it does at night, it may accelerate the restoration of leaf turgor, and in the morning can delay the onset of renewed stress (Slatyer, 1967). In arid regions, dew may therefore be beneficial to plant growth and make a positive contribution to the water balance of the plant.

Under conditions of low rainfall, the leaf structure of certain plant species has evolved to increase the amount of dew (or rain) absorbed directly into the shoot (Fitter and Hay, 1987). Slatyer (1967) mentions the possibility that dew may contribute to prolong survival, probably by reducing transpiration. However, Monteith (1963) estimates that these benefits are probably of little significance, as in cloudless summer days, in an arid climate, the ratio of potential condensation to evaporation is approximately 1:4.

Moreover, the severest stress for plants that are inadequately supplied with water occurs during the hottest hours of the day, long after the dew has evaporated.

Increasing dew condensation. In the Negev region of Israel, many hill sides are covered with regularly spaced heaps of stones (Fig. 2.3) that were probably built by the Nabateans, around the first centuries B.C. or A.D.; in Arabic, their name is Teleilat el Einab (grapevine mounds). This suggests that they were built to supply dew to individual plants, whose roots were beneath the stones. Monteith (1963) calculates that dew condensation from these mounds may have amounted to as much as 2–3 litres per night. Considerable doubts have, however, been expressed as to whether dew collection was really the function of these mounds.

In the Crimea, much bigger stone piles have been found on the hills above the port

of Theodosia. The potential calculated yield from condensation on them is 300 litres per night (Monteith, 1963).

In the sandy areas of the Negev Desert, it was found that a layer beneath the surface was moist in the cool morning hours, in spite of the dry, rainless season. This transient condition of soil–air moisture was attributed to differences between day and night temperatures in the upper 3–8 cm soil layer (Boyko et al., 1957). This observation may add credence to the view that stonemounds were capable of condensing significant amounts of dew.

Fog

When a warm, saturated air mass replaces a cool, dry air mass over a cool surface, fog or mist results. During overcast nights, this may cause the deposition of relatively large amounts of water on plants and on the soil surface (Long, 1958).

Fog is of very frequent occurrence along rather narrow coastal regions which border on oceans with cold currents that run parallel to the coast. It affects plant growth through the high air humidity, through wetting of the aerial parts of plants, and through humidification of the surface of the soil (Emberger and Lemée, 1962). There are no accurate measurements of the amount of moisture supplied by fog to the hydric balance of plants, but both type and density of vegetation appear in places to be influenced by the frequency of fog occurrence.

Frequent fogs or mists, by reducing evapotranspiration, may considerably increase the effective humidity of a region without this being reflected in the various formulae devised for defining aridity (Troll, 1958). In certain deserts, in which no precipitation may fall for several consecutive years, vegetation types occur which derive their entire water requirements from fogs or mists. Typical regions of this nature are the Atacama desert in northern Chile and Peru (cf. Fig. 1.6) and the Namib desert in southern Africa (cf. Fig. 1.3).

Atmospheric water content

The most common expression of atmospheric water content is relative humidity; vapour pressure deficit is also used.

Relative humidity. Relative humidity (RH) has a considerable effect on evapotranspiration and hence on water requirements of crops. The close relationship between transpiration and physiological processes in the plant will be discussed in Ch. 5. When radiation is strong, and temperatures are high, low RH can restrict plant growth significantly.

In the dry regions, RH tends to be low, a mere 12–30% being common around mid-day (Trewartha, 1954). The low humidity, combined with high temperatures, increases the difficulties of maintaining an adequate water supply to crop plants. Transpiration may increase to a point at which water potential and plant turgor are reduced to below the critical level, even when soil moisture is adequate. Under these

conditions, increasing RH (by overhead irrigation, e.g.), may have a beneficial effect on yields.

Excessively high RH may also have detrimental effects on crop plants. With increasing RH, transpiration decreases, and the reduction of the heat load on the leaves becomes almost completely dependent on thermal radiation and removal of heat by convection currents. A combination of high RH and lack of air movement can cause serious crop damage.

The reduction of transpiration caused by high RH, retards the flow of water through the plant, thereby reducing the supply of minerals and the transfer of hormones synthesized in the roots, to its various organs. Under extreme conditions, the mineral and hormonal balance in the plant may be adversely affected.

Absolute atmospheric humidity is not always low in arid regions; because of the high temperatures, desert air may contain a considerable quantity of water vapour. Dews that occur during the cooler nights may, however, attenuate atmospheric dryness – at least if they are substantially absorbed by plants. A high relative humidity may partially compensate for low rainfall in regions with prevailing onshore winds from the sea.

In the semi-arid areas, there may be considerable variations in relative humidity, which tends to be dependent on the direction of the prevailing winds.

Vapour pressure deficit. Vapour pressure deficit, as an expression of atmospheric water content, is of more practical application; it relates more to the drying power of the atmosphere than RH, and is therefore related to evapotranspiration (Hatfield, 1990). High rates of evaporation, coupled with low and variable rainfall in the semi-arid tropics often lead to intermittent drought periods that may have serious implications for the stability of crop production (Kanemasu et al., 1990).

Solar radiation

More than 99% of the total energy input of the world comes from solar radiation. Nearly half of this is directly converted into heat, 23% energizes the processes of evaporation and precipitation, and about 0.02% is utilized in photosynthesis (Vinck, 1975).

The difference between the amount of radiation that comes from the sun, and the amounts of energy returned to the atmosphere and to space, is called *net energy*, which determines air and soil temperature, the rate of net photosynthesis and photomorphogenesis.

*Light**Potential productivity of dry regions*

The large amount of sunshine is the greatest potential asset of the desert regions for agriculture, and may reach 75–90% of the possible sunshine. Even during the winter months in the semi-arid areas, with winter rainfall, sunshine is plentiful. The hot and mild-arid and semi-arid regions of the world are better endowed with long hours of bright sunshine, combined with moderately high temperatures, than are any other parts of the world.

To a large extent irrigation can control the moisture régime of extensive areas, but the energy régime cannot be modified economically, except under the very limited conditions of greenhouses (Slatyer, 1967). Therefore, if an ample water supply can be provided by irrigation, yield levels can be achieved that are higher than in any other region (Davidson and Philip, 1958). This higher potential productivity is reflected by the figures in Table 2.5.

The major arid and semi-arid regions of the world are generally found between latitudes 20° and 30° in each hemisphere, with extremes often lying far outside these limits. The figures in Table 2.5 reflect the great agricultural productive potential, per unit area, of these regions.

In Fig. 2.4 the seasonal changes in the rate of net dry-matter gain per unit leaf area (E) for sunflower plants grown in four different climates, have been predicted from multiple regression on light and temperature (Warren-Wilson, 1969). That author has calculated that the annual dry-matter production of widely spaced sunflower

TABLE 2.5

Potential productivity of different regions of the earth (adapted from De Wit, 1967)

North latitude (degrees)	Number of months with mean temperature above 10°C	Carbohydrate/ha/year (in kg $\times 10^3$)
70	1	12
60	2	21
50	6	59
40	9	91
30	11	113
20	12	124
10	12	124
0	12	116
–10	12	117
–20	12	123
–30	12	121
–40	8	89
–50	1	12

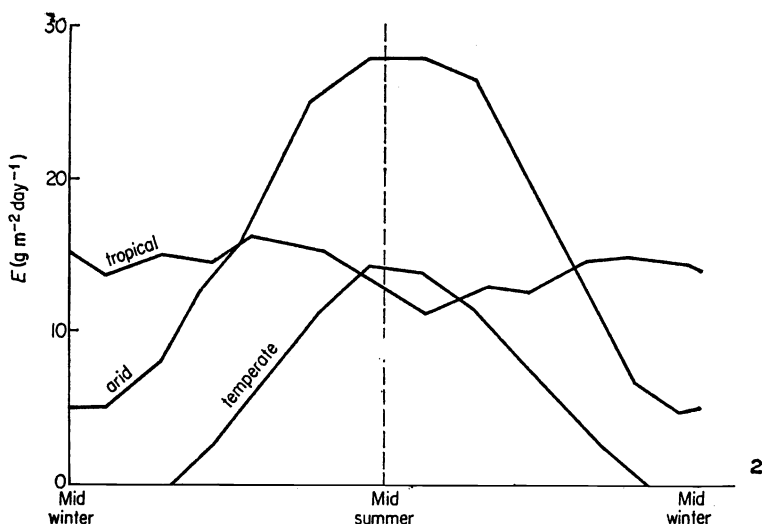


Fig. 2.4. Seasonal changes in the rate of net dry-matter gain per unit leaf area (E) for sunflower plants, predicted from multiple regression on light and temperature, for three climates. From Warren-Wilson (1969). By permission of International Potash Institute, Berne.

plants, when nutrient and water supply are non-limiting (expressed on a leaf-area basis), are as follows:

Arctic (Resolute, N.W.T., Canada)	$670\ g\ m^{-2}\ yr^{-1}$
Temperate (Kew, England)	$2170\ g\ m^{-2}\ yr^{-1}$
Tropical (Benin City, Nigeria)	$5110\ g\ m^{-2}\ yr^{-1}$
Arid (Deniliquin, N.S.W., Australia)	$5522\ g\ m^{-2}\ yr^{-1}$

Extremely high values of net dry-matter gain per unit leaf area have been found to occur in plants growing in the arid zones around latitude 30° in summer, when clear skies, fairly long days, and a sun rising high in the sky, combine to give more light than in any other climate. Provided soil nutrients and water are not limiting, it is in the arid regions that the greatest annual crop production is possible, as the mean annual light receipt in the 20° – 30° latitudinal zone is slightly higher than at any other latitude.

Light characteristics

Light is the electromagnetic part of radiation energy; the three characteristics of light which affect plant growth and development are intensity, duration, and quality (wavelength).

Light intensity. Light is the most important factor influencing the photosynthetic activity of a crop, as it is the energy source for the whole process. Changes in light

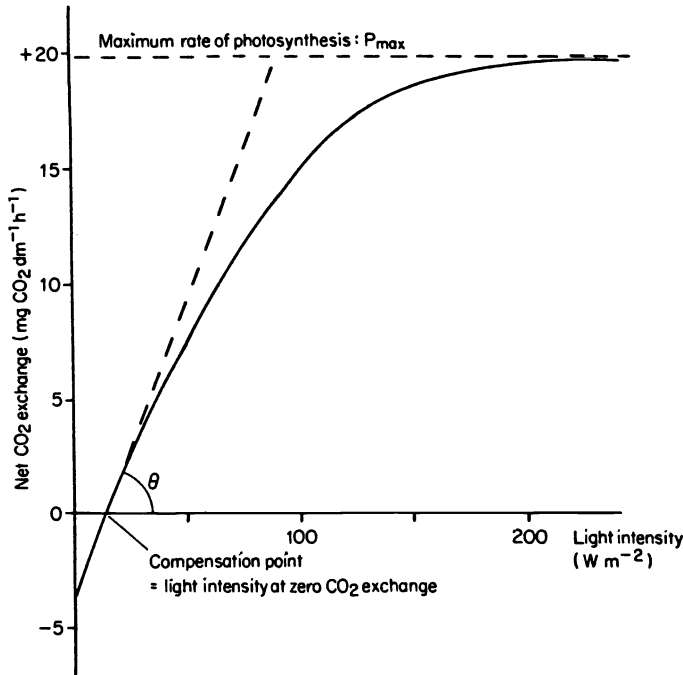


Fig. 2.5. Representative photosynthetic response curve showing the compensation point, the light intensity at which net CO_2 exchange is zero, as the point at which gross photosynthesis equals respiration. From Fitter and Hay (1987). By permission of Academic Press, New York and the authors.

intensity therefore have a greater impact on photosynthesis than on plant processes that use light as an environmental indicator (Fitter and Hay, 1987).

Light utilization by the crop has two limitations: the maximum quantum yield at low intensities and light saturation at high intensities (Loomis et al., 1967).

Minimum light requirements. It has generally been found that at low light intensities, for the individual leaf, there is a linear relation between light intensities and rate of photosynthesis. Theoretically, photosynthesis is possible at any light intensity, however low; practically, respiration dominates when light intensity is too low. Net assimilation will be zero at a light intensity of 500 candles, and a minimum of 500 to 1000 foot candle is required for effective rates of photosynthesis, at which the photosynthetic gas exchange is greater than the respiratory gas exchange (Blackman and Black, 1959).

Compensation point. The point at which assimilation gains equal respiration losses is known as the compensation point (Fig. 2.5). The problem faced by plants growing under conditions of low light intensity is to maintain a positive carbon balance; i.e., to maintain net assimilation rate above the compensation point.

Under low-light stress the plant has three options (Fitter and Hay, 1987):

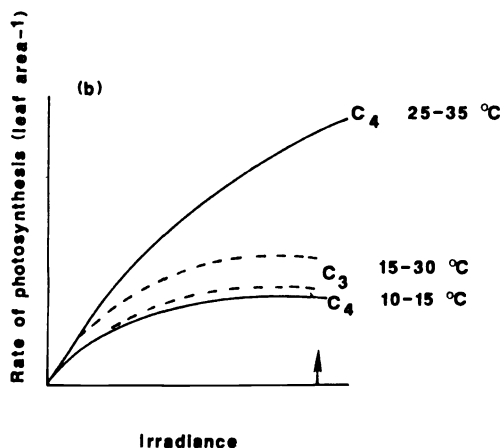


Fig. 2.6. Generalized typical photosynthetic light response curves for leaves of C3 and C4 plants at different temperatures. From Edwards and Walker (1983). By permission of the Commonwealth Scientific and Industrial Research Organisation, Melbourne.

- to reduce respiration rate, thereby lowering the compensation point; a small reduction in respiratory rate is a fairly general response of plants to low light intensity, but has little adaptive value excepting for plants normally growing in deep shade;
- to increase leaf area, in order to increase photosynthesis;
- to increase photosynthetic efficiency.

The two latter points will be discussed in Ch. 7.

Light saturation. Light provides the maximum input of energy on cloudless, clear days when the sun is at its zenith. However, for many crop plants, photosynthesis becomes saturated well below the maximum that they may experience, especially in the dry regions. C3 and C4 plants differ markedly in this respect (Fig. 2.6).

With increasing light intensity, photosynthesis of the single leaf obeys the law of diminishing returns. Extremely high light intensities even have an inhibitory effect on photosynthesis – a phenomenon called solarization (Wang, 1963).

In most crop plants, light saturation for single leaves is reached at a light intensity of $0.2 \text{ cal cm}^{-2} \text{ min}^{-1}$, which is typical of the light intensity on an overcast day with the sun at its zenith. On a clear day, light intensity may be four times as great (De Wit, 1967), so that a large proportion of the light is far in excess of what fully exposed leaves can utilize. For this reason, it was previously assumed that light could not generally become limiting for crop production.

However, in the field, light is not spread evenly over the photosynthetic surface but commonly passed by reflection and transmission through several layers of leaves, its intensity falling off exponentially with the path length through absorbing layers. The

fully exposed leaves in the canopy may absorb several times the amount of light needed for saturation, thereby absorbing a large proportion of the available light energy without increasing photosynthesis. The intensity of the light falling on the leaves in the lower layers depends on the initial light intensity, on the ratio between direct and diffuse light, on the number and size of the leaves, their angle of incidence, and distribution, and on the transmission and reflection of the leaves (Verhagen et al., 1963). At ground level, the final light intensity is usually below the compensation point, i.e., that light intensity at which the gas exchange resulting from photosynthesis is equal to that resulting from respiration (Bonner, 1962).

Very high light intensities are therefore rarely capable of saturating the whole canopy in the field, and the photosynthetic rate of the foliage *as a whole* continues to increase up to very high light intensities, as more and more leaves in the shaded parts of the canopy reach light saturation.

Light intensity and plant growth. The advantages of high light intensities enjoyed by the dry regions, are offset partially by shorter day length, warmer night temperatures with increased dark respiration and higher photorespiration rates during the day. As a result of this interplay of factors, C3 species perform better in temperate climates or cool seasons, and C4 species in the warm regions and summer conditions (Fig. 2.7).

The quantity of light energy required to regulate growth is different at different

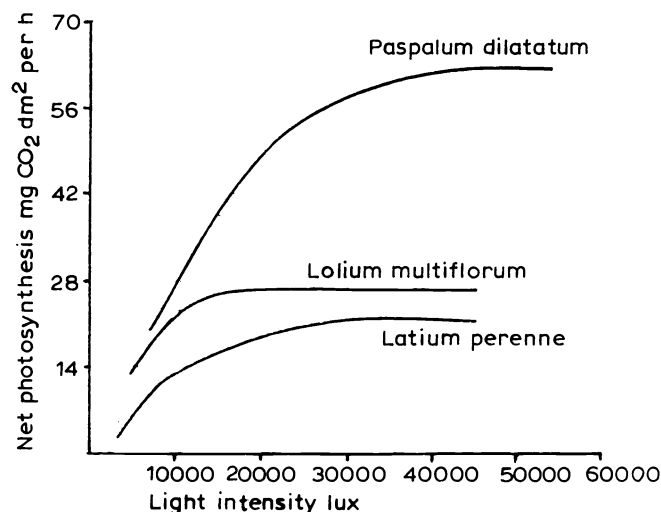


Fig 2.7. Specific examples of response of net photosynthesis to light intensity in *Paspalum dilatatum* (tropical, C4) and *Lolium multiflorum* and *L. perenne* (temperate, C3). From De Jaeger (1968). By permission of the Welsh Plant Breeding Station, Aberystwyth. The percentage conversion of light energy of the tropical species is similar to that of the temperate species at low light intensities, but considerably higher at high light intensities.

stages of growth. In many cases, and in particular in the dry regions, the high amounts of incident light required at certain growth stages by the plant may have undesirable side effects (McDaniel, 1982).

Light intensity and crop yields. Evans (1973) separates the effects of light on yield into two periods:

- during early vegetative growth and differentiation of storage organs;
- during the filling of the storage organs with assimilates.

Assimilates stored early in the life of the plant contribute little directly to economic yield (seeds, fruits, tubers) which is mainly dependent on concurrent assimilation (cf. p. 298). However, the early light environment may, indirectly, have important effects on yields by influencing characteristics which determine the potential storage capacity and the timing of the development cycle in relation to seasonal changes in radiation.

In desert regions the skies are generally clear. This favours high insolation by day and rapid radiation by night. As a result of the heating of the land during the day, rising air currents are induced, producing the typical 'dust devils'. The warmed air often rises sufficiently high to be cooled to dew point and form clouds; these may result in precipitation which, however, rarely reaches the ground. If and when it does reach the ground, the rain is usually local, torrential, and brief (Debenham, 1954).

When the sun shines through a gap in the clouds, the reflection from the clouds may, for a short period, increase and even double the intensity of incoming radiation, whilst a light cloud cover may completely intercept direct radiation, reducing it to zero (Slatyer, 1967).

Whereas overcast skies may reduce direct radiation, and diminish light intensity to about one-fifth of that of a clear sky, photosynthesis will not be reduced proportionally, because of the even distribution of the light (De Wit, 1967).

Shade. In the field, the main source of shade is the reciprocal shading of plants, and within plants, shading of lower leaves by those above them. The degree of shade depends on the amounts of light absorbed or reflected by the leaves.

Certain species have developed morphological and physiological mechanisms to cope with low light intensities. The so-called shade plants are more efficient in using low-intensity light than heliophytes; leaves of the latter are light-saturated when light intensity is about 30% of full light, whilst in shade plants photosynthesis continues at light intensities up to 10% of full light.

Light duration. Daylength effects. The duration of light is of major importance to the growth and development of plants. The effect of photoperiodism – the relative length of daily light and dark periods – on the vegetative and reproductive stages of development is well known. Plants have been classified on the basis of their photoperiodic requirements for floral initiation into long-day (usually more than 14 hours),

short-day (less than 10 hours), day-neutral, and indeterminate (requiring 12–14 hours of light daily to initiate flowering).

Length of day is largely a function of latitude. At the time of the equinoxes, the length of day is practically the same at all latitudes. At the beginning of summer, daylength between latitudes 10° and 30° is 13–14 hours; between 30° and 50° , in the middle latitudes, it is 14–16½ hours; at 60° it is approximately 19 hours.

Most typical tropical crops are short-day plants (requiring long nights for flowering), whilst those of higher latitudes are generally long-day plants.

The daylength that prevails in a given location at different periods of the year is the least variable of climatic factors, and therefore the most reliable predictor of the normal climatic conditions that will prevail at a given time of the year. Sensitivity to daylength (photoperiodism) enables plants to ensure that their life cycle corresponds as closely as possible to favourable climatic conditions, and therefore has great significance for agriculture. In this context, daylength is the dominant component of the light environment (Evans, 1973), and is the climatic factor with the greatest effect on crop adaptation to a given latitude.

The sensitivity to daylength may differ between varieties of the same species. Selection pressure to develop daylength neutrality in crop species, in order to widen their areas of production, has been very successful in a number of major crops. Varieties of maize, e.g., a typical short-day crop, have been developed for areas with long days.

Daylength influences not only the time of flowering, but also affects other growth stages, such as germination, stem elongation, leaf growth, tillering, leaf senescence and fruiting. Photoperiodic effects have been demonstrated for chlorophyll and anthocyanin synthesis in the leaves, the development of storage organs (sinks) in plants like onions and potatoes, seasonal leaf shedding in deciduous fruit trees, etc.

Some plants have different photoperiodic requirements for different developmental stages: wheat, e.g., is day-neutral for floral initiation, but generally long-day for fruiting (Evans, 1973).

Daylength or nightlength? Actually, a period of uninterrupted darkness at night, has a greater effect on plants than light duration during the day. Numerous experiments have demonstrated that shortening daylength by keeping long-day plants in the dark for several hours during daytime has had practically no effect on the time of flowering. By contrast, illuminating the plants at night, even for very brief periods, has a dramatic effect on flowering.

For example, when a short-day plant such as sorghum, is subjected to a brief interruption of darkness during the night, flowering that would normally have occurred, is prevented.

In the same way, it is possible to provoke flowering in long-day plants such as pyrethrum, e.g., during a short-day period.

Such manipulations have found many practical applications, enabling growers to control the time when certain high-value crops, such as flowers, will be ready for market.

There are several theories for explaining how plants 'measure' nightlength; a review of which is beyond the scope of this book.

Light quality

Photoreceptor systems. Responses to light are mediated by three major photoreceptor systems: *chlorophyll* (around 660 nm) for photosynthesis; *phytochrome R* (660 nm) and *phytochrome FR* (730 nm) for many photomorphogenetic responses; *carotenoids* for tropisms and high-energy photomorphogenesis.

Phytochrome is a protein pigment that occurs in plants at a far lower concentration than chlorophyll, but controls many photomorphogenic responses: dormancy and germination; leaf growth and unfolding, stem and root growth, plasmid differentiation, anthocyanin synthesis, flower induction (see below), and the response to many rhythmic phenomena (Evans, 1973).

Other pigments are found in plants capable of absorbing light, but their biological significance is generally not known (Fitter and Hay, 1987).

Wavelength bands. The term 'light' actually refers only to the visible portion of the electromagnetic spectrum which comprises a spectrum of colours: red, orange, yellow, green, and blue; however, all the wavelength bands of the spectrum are of concern to biologists. About one-third of solar radiation (400–700 nm) is photosynthetically active (PAR), with maximum absorption in the 435–675 nm range.

The *ultra-violet* (UV) wavebands are largely absorbed by atmospheric ozone; the greatly reduced UV radiation that reaches the plants is mainly absorbed by nucleic acids and proteins. Short-wave UV inactivates nucleic acids; these can be reactivated by the longer wavelengths (300–380 nm).

The visible region of the spectrum (380–780 nm) is strongly absorbed by leaves, especially in the *blue* (350–500 nm) and *red* bands (660 nm). In the green it is lower and more variable, ranging from 50–90% (Björkman, 1973).

Blue light has a dominant role in phototropism, the high-energy reaction of photomorphogenesis, and has significant effects on the stimulation of respiration, protoplasmic viscosity, stomatal opening, and protein synthesis (Evans, 1973).

The energy absorbed by leaves in the *infrared* (IR) region of the spectrum is not used photochemically, and has to be dissipated by transpiration, reflection, or convection. However, much of this radiation is absorbed by atmospheric water and CO₂, thereby considerably reducing the heat load on plants.

Sunlight provides an equal red/far-red ratio; this produces dark-green, well-developed plants (Cathey and Campbell, 1982).

Many factors, such as the amount and kind of cloud cover, fog, air pollution, and the colour of the foliage interrupting light, influence the quality of the incident light. For example, chlorophyll selectively removes the red while transmitting most of the far-red, so that plant organs under a canopy of green leaves are exposed to a low red/far-red ratio and are pale-green, spindly and poorly branched (McDaniel, 1982).

Photomorphogenic responses. Light controls all stages of growth, from germination to flowering; it has both direct and indirect biological effects; it affects plant metabolism directly (photosynthesis) and indirectly (growth and development).

Seed germination. The majority of the seeds of cultivated plants germinate equally well in the dark as in the light. However, there are many cases of specific requirements, for both light quantity and quality.

Many small-seeded species require light for rapid germination, but only in very few cultivated species is germination inhibited by light. The major significance of light effects on germination is therefore related to the incidence of weed infestations of cultivated fields.

The seeds of many weeds, especially those that are small-seeded, when buried deep by ploughing, will not germinate until they are brought to the surface by subsequent tillage operations. This explains why tillage operations are usually followed by a flush of germination of weed seeds (Klingman, 1985).

The mechanism that controls light-induced germination is the photoreversible activity of phytochrome. When this pigment is activated by red light, germination is induced, whereas far-red light changes the pigment into an inactive form, thereby preventing germination.

A crop with a closed canopy remains free of weeds that have light-stimulated germination because the foliage absorbs much of the red region of the spectrum, whereas much of the far-red light passes through, so that phytochrome is thereby maintained in the inactive form (Cathey and Campbell, 1982).

Phototropism. The controlling pigment for phototropism is still uncertain. Possibly carotenoids and flavins are involved (Evans, 1973).

Etiolation. Dicotyledonous seedlings, in the absence of light, respond by rapid elongation of the hypocotyl, whilst development of primary leaves and epicotyl is depressed. By contrast, seedlings develop a compact growth in response to red light: the first leaves increase in size and the epicotyl develops rapidly. By using photosynthate reserves for stem elongation, etiolation increases the probability that seedlings will reach the light.

In older plants, the tendency to etiolation as a result of light stress, is mitigated by the concomitant reduction in photosynthate production.

Flower induction. Most plants require a period of light, in combination with temperature and CO₂, of days to weeks duration, to induce flowering (see photoperiodism). Within most species appear genotypes that divert from the specific requirements of the species (Cathey and Campbell, 1982).

The red/far-red reversible pigment phytochrome plays a major role in mediating induction in both short-day and long-day plants.

Root growth. Root growth is markedly affected by light: low light intensities reduce the root/shoot ratio through a deficient supply of assimilates. However, reduced root

activity limits the supply of water and nutrients to the shoots; this feedback system ensures at least a minimum supply of nutrients to the roots (Evans, 1973).

Crop management for efficient use of light

A major objective of crop management is to maximize light interception by the crop canopy. This can be achieved in various ways (EUROCONSULT, 1989):

(a) Choice of location. For example, the hillside with maximum exposure to sunshine is obviously the best location for a vineyard, and is a major factor in productivity and in the quality of the wine produced. Conversely, one or several rows of trees may have a significant effect on the amount and intensity of light reaching the crop in an adjacent field.

(b) Adapting plant population density and row orientation is one of the major practices available to the farmer to maximize light interception by the crop canopy (cf. Ch. 14).

(c) Pruning. Competition for light between different parts of the plant, as well as between plants, can be attenuated by pruning, as widely practiced in many horticultural crops.

(d) Artificial lighting can be used for increasing photosynthesis or regulating photoperiodism. Photosynthesis requires considerable light energy, and artificial lighting for this purpose is seldom economically justified. By contrast, regulating photoperiodism requires low inputs of electricity, and is widely used, especially in floriculture, to ensure that flowers are ready for marketing at the most favourable times.

(e) Alternatively, the provision of shade may be required by certain crops such as coffee or cacao, that are grown under the canopy of suitable tree crops. Tobacco for cigars is grown under shade provided by a special cloth cover. Sometimes it is desirable to prevent light from reaching parts of the plant, as in the case of celery or asparagus, in order to 'bleach' the marketable product. This is done by ridging the soil on the plant rows.

Plant breeding for high yield is concerned with manipulating physiological and morphological plant traits that improve photosynthetic efficiency.

Among cultivated plants, it has often been necessary to modify plant response to photoperiodism. An important goal of plant breeders has often been to modify photoperiodic responses in the direction of indifference to daylength, in order to widen the range of adaptation of a cultivar.

In view of their importance in crop production, most of these topics will be treated in detail in the appropriate chapters.

Temperature

Temperatures in the hot, arid climates are the highest in the world (Critchfield, 1966). The generally clear skies facilitate maximum radiation by day and rapid loss of heat by night – resulting in high diurnal ranges of temperature, which may reach 30 to 40°C in the hot deserts during the summer.

The sparse vegetative cover permits the soil surface to become intensively heated by day, with temperatures at the soil surface reaching 93°C (Trewartha, 1954). The higher the temperature of a body, the more rapidly it loses heat by radiation. Deserts, therefore, both acquire and lose heat very rapidly. At night, about 90% of the heat accumulated during the day is radiated into space, as compared with 50% in humid climates (Cloudsley-Thompson, 1954).

The seasonal variations in temperature increase with the distance from the Equator; however, within the semi-arid areas, temperature is not as variable as precipitation. The position of the sun is the major factor controlling seasonal variations in temperature; local factors, such as elevation, prevailing winds, cloudiness, distance from large bodies of water, natural ground cover, also influence these variations (Hatfield, 1990).

The annual ranges of temperature are less marked in hot deserts than in many other regions, but are far greater than in the humid tropics. Daily average ranges during the hottest months in the hot desert area are 27–35°C, with daily maxima of 37–43°C. The coolest months in these areas average around 10°C, with occasional night frosts. Temperatures in the semi-arid hot climates are generally similar to those of the more arid regions (Critchfield, 1966).

In the middle-latitude dry regions, the annual range of temperatures is far greater than in the other dry regions, with extremely low temperatures in winter and very hot summers.

Cardinal temperatures

In contrast to homeothermic animals, plants are not able to maintain an optimal temperatures in their cells and tissues, and therefore the temperatures of their leaves, stems and roots are in balance with that of the air or soil surrounding them.

Plants can grow only within certain limits of temperature. For each species and variety, there are three levels of temperature known as cardinal temperatures: *minimum*, below which growth ceases; an *optimum range*, the most favourable for growth (in practice the range of temperatures over which the rate of growth or of a metabolic process is within 10% of the maximum rate (Fitter and Hay, 1987); and *maximum*, above which growth ceases. Heat-killing temperatures vary inversely with the duration of the exposure to high temperatures; the relationship to duration is exponential (Levitt, 1972).

Lange (1956) found that most plants in the Sahara desert survived excessively high temperatures only when sufficient water was available to support a high transpira-

tion rate. However, it was impossible to grow certain plants in an oasis in summer, even with plentiful watering, because of heat injury.

There are also different optimal temperatures for different growth stages and functions, as well as lower and upper lethal limits.

Temperature therefore determines the nature of the vegetation in a region, and also defines the climatic boundaries within which production of a crop is possible.

Temperature effects

Biochemical plant processes. Temperature influences all chemical and physical processes in the plant, from solubility of mineral and organic solutes in its tissues, to the most critical physiological processes in plant life.

Solubility generally increases with rising temperatures; carbon dioxide is an exception, its solubility in cold water being double of that in hot water.

The diffusion of gases and movement of liquids through the plant increases as temperatures rise, though not always linearly. For example, an excessive concentration of metabolites can cause the cessation of photosynthesis, even when the temperature is favourable for the process.

Temperature affects the activity of enzymes and their stability. At optimal temperatures, enzyme systems function efficiently, and remain stable for relatively long periods; at low temperatures, they still remain stable, but their activity declines and eventually ceases.

Most biochemical processes *in vitro* proceed more rapidly as temperature increases; however, in the plant cell these reactions depend on catalytic enzyme activities.

In the range between lethal and suboptimal temperatures, stability of the enzyme systems is only marginally affected, and the biochemical processes accelerated by rising temperatures; above optimum, a slight increase in temperature accelerates the breakdown of enzymes and indirectly a slowdown of the reactions.

Temperature affects the ratio of different metabolites in plant organs: in many crop plants, as winter approaches and temperatures decline, sugar content decreases and fat or starch content increases; the reverse process occurs with rising temperatures as spring approaches.

The uptake of water and its solutes improves in the range between minimum and optimum temperature, because the viscosity of water decreases, the permeability of cell walls increases and root growth is accelerated.

Photosynthesis. We have seen that light has an overriding effect on the rate of photosynthesis. However, it is involved in only one aspect of the photosynthetic process, namely, as a source of energy for the conversion of carbon dioxide and water to carbohydrates.

There are certain biochemical processes preceding and following the reduction of carbon dioxide, which are affected mainly by temperature (Gaastra, 1963). As long

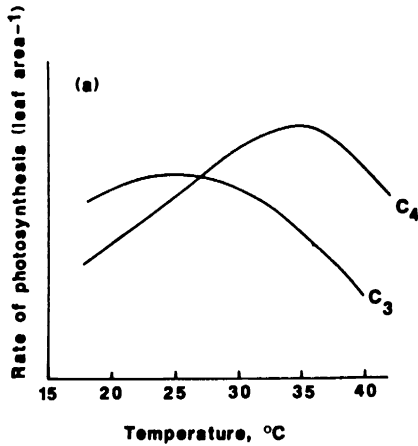


Fig. 2.8. Generalized typical temperature response curves for photosynthesis in leaves of C3 and C4 plants. From Edwards and Walker (1983). By permission of the Commonwealth Scientific and Industrial Research Organisation, Melbourne.

as light is limiting, temperature has little effect on the rate of photosynthesis. However, when light is not limiting, as is generally the case in dry regions, the biochemical processes associated with photosynthesis become the limiting factor, so that the effect of favourable temperatures on the rate of photosynthesis is increased.

Photosynthesis often shows a suboptimal range, a fairly wide optimum, and is extremely sensitive to heat.

Temperature responses in temperate and tropical crops, and in particular between C3 and C4 species differ considerably (Figs. 2.8, 2.9).

In Table 2.6 cardinal temperatures for net photosynthesis are shown for C4 and C3 species, respectively.

There is considerable variation within each group and species, with genotypes adapted to local environments. Respiration is far less affected by heat than photosynthesis, so that at temperatures above optimum the net assimilation rate declines

TABLE 2.6

Cardinal temperatures for net photosynthesis (°C)

	$T_{\min}$	T_{opt}	$T_{\max}$
Tropical C4 species	5–7	35–45	50–60
C3 crop species	–2 to >0	20–30	40–50

Source: Larcher (1975).

rapidly. Similarly, suboptimal temperatures cause a decline of net photosynthesis until a critical temperature is reached, at about 10–12°C (Larcher, 1981).

Crop distribution. The length of time required for completion of the annual growth cycle increases as the climate becomes cooler, so that there is a critical mean temperature below which crops of a given species cannot reproduce successfully. For example, maize is not grown for grain production where the mean summer temperature is less than 19°C, and where the average night temperature during the summer months falls below 13°C (Shaw, 1955). However, breeding has extended this range markedly.

Vernalization. In addition to influencing plant metabolism and growth, temperature also controls development in certain crop species. For example, winter cereals are unable to flower until they have been vernalized, i.e., have experienced a period of low temperature. This adaptation ensures that flowering does not begin until after the period of temperatures that are unfavourable to flowering has passed.

Effects of extreme temperatures. Ability to tolerate extremes in temperature often defines the range of a crop species. The upper limit of growth occurs at the point of protein denaturation, which effectively disrupts the enzymatic machinery of the cell; the lower limit for growth occurs at the point of intercellular ice formation; ice

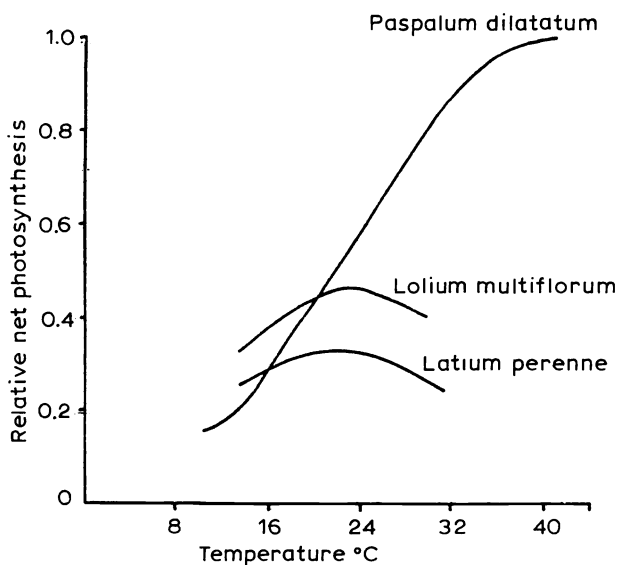


Fig. 2.9. Response of net photosynthesis to temperature in *Paspalum dilatatum* (tropical, C4) and *Lolium multiflorum* and *L. perenne* (temperate, C3). From De Jaeger (1968). By permission of the Welsh Plant Breeding Station, Aberystwyth. In the tropical species, net assimilation rate (NAR) remains very low until a temperature of 15°C is reached, and then increases rapidly up to 35° and above; by contrast, the NAR of the temperate species reaches a maximum at about 20°C.

disrupts the continuity of protoplasmic gel and blocks the passage of hormone messages and metabolites necessary for cell growth and division (McDaniel, 1982). Both extreme heat and extreme cold can be lethal to crop plants. For example, in the northern Great Plains of the USA, loss or damage of fall-sown wheat can occur from excessive cold in winter, or from extreme heat (frequently combined with dryness) in summer (Steiner et al., 1988).

Non-freezing temperatures and frosts. Warm-weather plants such as maize, are sensitive to chilling at temperatures ranging from 0 to 6°C, though physiological damage may be caused to seedlings exposed to temperatures below 16°C. The severity of the injury depends on the temperature and the duration of exposure. Short periods of cool temperature (cool nights) are generally not harmful. The sensitivity to chilling increases with the stage of seedling development. High light intensities increase the sensitivity to low temperatures (Miedema, 1982).

Chilling injury. Because of the great economic value of crop plants of tropical and subtropical origin, there is considerable interest in their degree of susceptibility to chilling injury. Chilling injury may occur from the point of seed hydration, throughout the growth and development of the crop and during postharvest storage (McDaniel, 1982).

Numerous changes occur in plant tissues as a result of chilling stress; among these one of the most frequent is damage to cellular membranes, altering their permeability and resulting in loss of solutes. This process is known as electrolyte leakage, and involves loss of sugars, amino acids, organic acids, proteins, and other solutes. Electrolyte leakage also occurs as a result of freezing or heat stresses (McDaniel, 1982).

Chilling injury results in poor seedling establishment, stunted growth, wilting, chlorosis, necrosis, poor fruit set, etc. (Blum, 1988). Low temperatures reduce germination, seedling emergence and subsequent growth. At temperatures which delay or slow down germination, several species of fungi are active; the germinating seed and the seedlings are therefore easily infected by soil- and seed-borne pathogens.

Low temperatures in spring prevent the early sowing of warm-season crops; the resultant delay reduces water-use efficiency, does not allow the crop to escape excessively high temperatures at flowering, and may delay harvest until after the first rains or killing frosts. Hence the considerable effort invested in breeding for germination and seedling establishment at low temperatures in maize, e.g. Success in this objective has also made it possible to extend maize production northwards. Chilling temperatures frequently cause pollen sterility in crop plants, such as rice, sorghum, and tomato, deformation of flowers or fruit, and poor fruit colour (Blum, 1988).

In some cases, it is possible to alleviate, or largely eliminate damage caused by chilling, by preconditioning the seed (McDaniel, 1982) (cf. p. 71)

Freezing injury. The clear skies at night permit considerable radiation from the earth in arid regions. The rapid cooling of the land at night causes an inversion of temperature, the air near the cool soil becomes heavy and does not rise, so that night temperatures at soil level are typically low in the desert and many reach freezing

point, even after a relatively hot day. Cold air will tend to flow into low places, so that localized pockets of frost may occur in an area which is generally frost-free. In the middle-latitude dry zones, the incidence of killing frosts determines the length of the growing season, which is practically limited to the time interval between the last killing frost of spring and the first killing frost of autumn. The shorter this period is, the earlier maturing will be the varieties that can be grown and the lower their potential yielding ability. In the arid regions with mild winters and no or rare frosts, it is possible to produce two, and sometimes three, crops a year. The annual number of cuttings of a perennial forage crop, such as lucerne (alfalfa), varies from three (in a region with killing frosts) to ten (in a region with mild winters).

In warm regions, occasional and exceptional frosts may do considerable damage because the crops grown in such regions are usually very susceptible to low temperatures.

Freezing temperatures are responsible for enormous losses of agricultural produce. Freezing stress results when the plants are subjected to subzero temperatures. A crop that is sensitive to frost, such as maize, can suffer injury during all phases of its growth, except as dry seed. Genetic variation appears to be very small (Miedema, 1982).

During slow freezing, unprotected cells from even potentially hardy plants die as a result of water stress due to the conversion of intracellular water to extracellular ice, rather than to mechanical damage or temperature stress. Cellular membranes lose their semi-permeability when certain intracellular solutes accumulate to toxic levels.

Freezing survival depends on a dessication process of the plant tissues, which involves the thickening of cell sap, a process termed 'cytoplasmic augmentation' (McDaniel, 1982).

High-temperature injury. In arid lands dryness and high temperatures are generally associated with each other. Because of the high net radiation and the little water that is available for evapotranspiration *resistance to heat* by the plant plays a very large role (Emberger and Lemée, 1962). The resistance of plants to heat is accordingly just as relevant to their adaptation to arid conditions as is their resistance to drought; when irrigation is practised, heat-resistance becomes the main consideration.

Plant tissues dissipate heat by three main processes: emission of long-wave radiation, convection of heat, and most important, transpiration.

The effects of high-temperature stress on crop plants are therefore closely linked with the water status of the plant. Wilting, leaf burn, leaf folding, and abscission are all indicators of water stress, but also serve as early indicators of high-temperature-induced damage, especially during periods of rapid leaf growth and expansion (McDaniel, 1982).

The simplest kind of metabolic injury due to heat is starvation, because of the higher optimum temperature for respiration than for photosynthesis. The temperature at which photosynthesis and respiration are equally rapid is called the *temperature compensation point* (Levitt, 1972). When plant temperatures rise above the com-

pensation curve, the reserves are depleted, and if the temperature stress continues, ultimately death due to starvation will result.

Damage caused by high temperatures as a result of physiological disorders, resulting in death of cells, tissues, organs, or whole plants, is common in crop plants (Blum, 1988). However, most often excessive heat slows growth rather than causing death of the plant. High heat is a growth constraint in the low-altitude tropical and subtropical regions, with a short or non-existent cool season, as well as in the higher latitudes with continental climate characterized by short, very hot summers.

Sun-scald is typical for organs which lack transpirational cooling, when temperatures on the surface of the organ may reach 48–50°C (Peacock, 1982).

Seedlings are especially sensitive to high temperatures, and are frequently killed, either by heating of the whole seedling, or by contact with hot soil.

Excessive heat causes flower abscission, pollen sterility, and poor fruit set resulting in reduced yields.

Retardation of growth and difficulties in fertilization, even in heat-loving crops such as maize and sorghum, occur at temperatures that are often well below the lethal limit. The harmful effects of excessive temperatures are usually aggravated by lack of available moisture. Hot, dry winds will further increase the damage.

In the Great Plains of the USA, it was found that high summer temperatures may even override the effects of summer rainfall on the yields of crops. Thus variability in yields of spring wheat was clearly associated with variability in average maximum temperatures in June, and variability in maize yields was most closely associated with variability in average maximum temperatures in July (Moldenhauer and Westin, 1959). With increasing temperatures, evapotranspiration increases. Hence, a moisture supply that is adequate in a cooler climate may be deficient in a warmer region – a situation which may be aggravated by hot winds.

High temperatures cause a rapid breakdown of enzymes. For example, an enzymatic system that functions efficiently at the temperature of 28°C will continue to function for only 30 minutes at 30°C, and will cease to function after a few seconds at 38°C (McDaniel, 1982).

Pre-conditioning. The cardinal temperatures of a plant may change as the result of stress to which it has been subjected at certain growth stages. For example, in a plant that has been subjected to relatively low temperatures for a number of times, various biochemical and physiological changes occur; as a result, the plant will be more resistant to a lethally low temperature than if it had grown continuously at favourable temperatures, a phenomenon known as pre-conditioning, and in the case of low temperatures, as frost-hardening.

A degree of frost resistance can be acquired by certain crop species when submitted to hardening conditions early in winter; this resistance is usually lost by 'dehardening' when dormancy is replaced by active growth in the spring.

A similar process occurs after exposure to high temperatures, which allows the plant to better withstand a subsequent period of high-temperature stress.

Heber and Santarius (1976) describe a number of possible mechanisms of membrane protection to account for hardening. Basically, the protection is provided by an accumulation of sugars and their derivatives, which reduce, during freezing, the concentration of potentially membrane-toxic compounds.

Thermoperiodism. Changes in temperature between day and night are most extreme in arid regions. Many plants have adapted to the daily alternation of day and night, with its attendant change in climate parameters, and their growth is adversely affected when grown in an artificial constant environment.

The response of plants to changes in day and night temperatures is called thermoperiodism. Germination, in particular, is most sensitive to these changes. Other functions that are favourably influenced by the daily alternation of day and night temperatures are stem elongation, opening of flower buds, fruit set, etc.

Flowering in soya is improved by high temperature and short day; sugar beet requires the opposite conditions of low temperature and long day. The reason for the favourable effect of thermoperiodism on certain plant functions is due to the fact, already mentioned, that optimum temperatures may be different for different biological processes.

An unchanging temperature may be favourable for one process and unfavourable for another, equally important process. The regular daily change of temperature may provide optimum conditions at night for one process, and during the day for the other, so that both processes can proceed under optimal conditions.

Crop management in relation to temperature

The choice of an appropriate site for frost-sensitive crops may be critical for the survival of the crop or for its productivity. Various preventive measures are available to the farmer to prevent frost damage, such as creating artificial fog (by burning old tyres, e.g.), heating, overhead irrigation, etc.

Crops can be grown throughout their life, or only during susceptible periods, under various types of cover, which provide (a) protection against the cold, (b) accumulate heat during the day which keeps the plants warm at night, or (c) have a source of heat which can be adjusted to outside temperature.

These protective covers range from the most simple, where plants are individually covered by small plastic caps, to sophisticated glass or plastic-covered buildings with computer-controlled environments.

Winds

The arid regions are under the influence of winds which originate either over the sea

or over deserts. In summer, the desert regions become heated to high temperatures; the heated air rises, causing an indraught of winds from neighbouring regions. If these winds pass over an ocean, they become moisture-laden. These are the monsoon winds, such as those that invade the Sahara from the south-west during the northern summer.

During the winter, the opposite effect occurs: the desert areas are cooler than the adjacent tropical areas, and the winds blow from the desert towards the tropical areas. These winds are relatively cool and dry at the beginning of the growing season, but become progressively hotter and drier as the spring advances. They are called Harmattan in most of tropical West Africa north of the Equator and Khamsin in the Near East.

The arid regions are characterized by frequent and strong winds, which are due partly to considerable convection during the day. The usually sparse vegetation is not capable of slowing down air movement, so that dust storms are a frequent concomitant of wind movement. Much of the dust is carried for considerable distances, to form loess deposits in neighbouring regions. The heavier sand particles carried by the wind scour the soil surface.

The Harmattan of West Africa north of the Equator, e.g., a dry, dust-laden wind of the winter season can carry yellowish dust westward over the Atlantic as far as the West Indies (Matlock, 1981).

Effects on crop plants

Mechanical

Physical damage to plants caused by blowing sand can be a serious problem in certain areas (Steiner et al., 1988). Emerging seedlings may be completely covered or, alternatively, the roots of young plants may be exposed by strong winds. Winds may also cause considerable losses by inducing lodging, the breaking of stalks, and shedding of grain.

Strong winds can damage fruit and cause fruit drop, cause loss of grain by lodging and shattering, and adversely affect flowering and fruiting of crops. Winds also transport insects, disease organisms, weed seeds, and pollen.

Physiological

The physiological effect of winds consists mainly in increasing evapotranspiration, thereby increasing plant water use and plant water stress.

The effect of wind speed on transpiration rates depends on the amount of radiation absorbed by the leaves. When absorbed radiation is low, an increase in wind speed causes transpiration rates to increase; conversely, when it is high, the transpiration rate decreases with increased wind. Obviously, when conditions are intermediate, wind speed has no effect on transpiration rates (Gates, 1976).

Moderate winds have a beneficial effect on photosynthesis by continuously replacing the carbon dioxide absorbed by the leaf surfaces. When turbulence was low in a dense maize canopy, the maximum observed photosynthetic efficiency in the utilization of radiation was found to be 2%; efficiency was doubled to 4%, under conditions of high radiation, when turbulence provided sufficient carbon dioxide (Lemon, 1963). It was also found that photosynthetic efficiencies increased with increasing wind – even when the maize was visibly wilting as a result of water stress, and notwithstanding stomatal closure.

The favourable effect of wind on photosynthesis was most marked at the lower leaf layers; increasing wind strength permitted ever deeper leaf layers to approach the maximum rate of photosynthesis possible under the amounts of radiation received (Lemon, 1963).

Winds often increase the heat and cold stress of crop plants by enhancing desiccation (Steiner et al., 1988). Hot winds may adversely affect photosynthesis, and hence productivity, by causing stomata to close even when soil moisture is adequate (Crafts et al., 1949).

In the Near East, the Khamsin (or Sharkia) may blow for a limited number of days only, but the effect of these winds in spring on the crops and their yields may be considerable. Overnight, temperatures may soar from 25 to 46°C, and the relative humidity may drop to 5–10%.

If the cereal crops are earing when a Khamsin strikes, the ears may be actually ‘blasted’, turning white, without any seed formation following. When the Khamsin occurs at a later stage, seeds may shrivel and mature ahead of time.

The hot, dry winds may also occasionally have beneficial effects. The main reason for the low incidence of the very dangerous yellow rust of wheat (*Puccinia glumarum*) in the Near East, is the susceptibility of the pathogen to the high temperatures that occur when the sirocco winds blow. In the rare years when no Khamsins occur in the spring season, this rust may cause devastating reductions in yield.

Soil erosion

Soil erosion by wind can be a major calamity in dry regions (Christiansen, 1982). This topic is treated in detail in Ch. 9.

Winds as a source of energy

The potential of wind as a source of energy in desert and semi-arid areas is currently receiving serious consideration. The most productive use of this energy would be for pumping water from underground aquifers or transport of urban sewage to the desert (Smith, 1979).

Carbon dioxide

The carbon dioxide content of the atmosphere is of major importance to plant growth. Photosynthesis is approximately proportional to the concentration of CO_2 in the air surrounding the foliage of the crop (Monteith, 1965). An important source of CO_2 is the decomposition of organic residues by micro-organisms, though 'soil respiration' is not sufficient to enable rapid rates of photosynthesis to take place (Moss et al., 1961).

Levels of CO_2 show a diurnal variation, the amplitude depending on the height above the canopy, with a maximum during the night (Bierhuizen, 1976).

Concentration in the atmosphere

The concentration of carbon dioxide in the atmosphere may vary locally very considerably, ranging from half to several times the normal value, which is around 0.03% by volume. In fields of dense, growing crops, when there is no wind, levels may fall well below 0.03%. However, decreases in photosynthetic rate due to a local deficit of CO_2 rarely exceed 20% (Monteith, 1965).

Carbon dioxide enrichment

Increasing CO_2 concentration, when economically justified, can have a considerable effect on crop yields, especially when high light intensities and favourable temperatures prevail at the same time.

Kimball and Idso (1983), after analyzing reports in the literature on a large number of experiments on CO_2 enrichment, found that a doubling of atmospheric CO_2 resulted in an average yield increase of 33%, and a reduction of transpiration of 34%. These data indicate that the combined effect would result in a doubling of water use efficiency.

Because CO_2 at high concentrations can close stomata, Begg and Turner (1976) have suggested that this might be useful in improving water use efficiency of crops.

In long-term growth chamber experiments, it was found that the relative yield increase resulting from CO_2 enrichment was practically the same for water-stressed wheat as for well-watered wheat (Sionit et al., 1980).

The greenhouse effect

Before the industrial revolution, the CO_2 concentration in the air was probable in the range of 260 to 290 ppm. The present value is approximately 340 ppm, or an increase of 25% (Bolin et al., 1979). This increase has largely been due to the unprecedented burning of fossil fuels. It is predicted that the concentration of CO_2 will double, possibly as early as 2025 (Gribbin, 1981).

Heichel (1983) writes: "Future increases in atmospheric CO₂ concentrations are virtually guaranteed, so there is every reason to believe that important modifications of crop growth and water use will ensue".

This increase could lead to substantially increased photosynthesis and crop productivity and improved water use efficiency; it could also, possibly, have catastrophic effects. CO₂ traps infrared heat, a condition known as the 'greenhouse effect'.

A significant increase in CO₂ concentration could therefore increase temperature, with a probable effect on precipitation. The efficiency of the photosynthetic process in crops would be increased, adverse effects on crop growth and production would, however, also be possible (Johnson, 1970).

In the light of the dearth of analytical understanding of how this environmental change will affect growth and development of crop plants, Heichel (1983) stresses the need for research to anticipate the problems that may ensue.

Microclimate

Microclimatology deals with the pertinent factors of the environment in the zone lying between the highest level affected by plants locally and the lowest depth to which air penetrates into the soil (D'Albe-Fournier, 1958).

Microclimate at plant level

The microclimate just above a crop and under its canopy (eco-climate) is influenced by the particular type of crop, and may be strikingly different from the climate of the surrounding environment. Even emerging seedlings will alter the climate near the soil surface, by reducing air movement and by shading the ground. As the plants grow, the extremes in temperatures of the soil surface are reduced; even so, the range of temperatures at the soil surface may be double that of the temperatures recorded in the standard meteorological screen.

The eco-climate may be more humid and cooler than the atmosphere above the crop, which circumstances may create favourable conditions for the spread of certain diseases. Leaf temperatures in the sunlight may be higher than the air temperature by day and lower than the air temperature by night. The intensity and quality of light change as the rays pass through the plant canopy.

Heat advection

Irrigated areas are usually isolated islands of above-normal moisture conditions, enclosed in a vast expanse of dryland. If warm air, from surrounding dry areas, passes over a cooler and moister irrigated area, the microclimate of the latter at plant

level will be influenced up to a down-wind distance of 80 to 100 m. This influence usually consists of the advection of sensible heat (Fritschen and Bavel, 1963) (the so-called *oasis effect*, Lemon et al., 1957). Advection has been defined as “the exchange of energy, moisture, or momentum due to horizontal heterogeneity” (Philip, 1959).

When the warm wind moves through a crop, it is cooled and supplies heat for evapotranspiration; this is known as the *clothesline effect* (Tanner, 1957).

In dry regions, evapotranspiration may be increased significantly, through advection of sensible heat (Fritschen and Bavel, 1963). In arid and subhumid climates, wind can contribute as much as half the energy consumed in evapotranspiration (Blad, 1983).

When air temperatures are high, and stomatal conductance is high, transpiring leaves may be cooler by 5°C than air temperature; conversely, if stomatal conductance is low, the temperature of the leaves may be 5°C higher than that of the air (Barfield and Norman, 1983).

Soil microclimate

The climate in the soil may be strikingly different from that of the atmosphere above it.

Soil albedo

Only part of the radiation that reaches the surface of the soil is absorbed, the amount reflected depending on certain characteristics of the surface of the soil. The percentage of the incoming radiation that is reflected is called the ‘albedo’, which varies according to plant cover, soil type, moisture content, etc., as shown by the figures in Table 2.7.

Thermal régimes

As a result of differences in albedo, different thermal régimes will exist on different

TABLE 2.7

Albedo of different soil surfaces (Thorntwaite, 1958)

Surface	Albedo (percentage of incoming radiation)
Wet sand	9
Dry land	18
Grass cover, green crops	15–30
Forest	15–18

types of soil surface layers and the air above them – even when the amounts of incoming radiation are identical. For example, a mulch on the surface of the soil absorbs most of the incoming radiation; the soil remains cool, whilst the surface of the mulch itself and the overlying air become very hot during the daytime and cool rapidly during the night hours.

The temperature of the top layer of the soil is usually higher than that of the overlying atmosphere, while daily fluctuations in temperature decrease with increasing depth in the soil. At a depth of 50 cm, daily variations of temperature in the soil practically cease (Migahid, 1962). At a depth of 1–3 m, temperatures are fairly stable throughout the year.

Soil temperature has considerable influence on plant growth and on the soil micro-organisms. Warm (20–30°C), moist soils are a favourable medium for most of the cultivated crops that are grown in arid regions.

Temperature effects

Germination. The temperature fluctuations mentioned above are important for several aspects of crop production, including germination. Some seeds require marked temperature variations for germination, others are sensitive to low minimum or high maximum temperatures. These requirements need to be taken into account when deciding on depth of sowing.

Plant growth. Following germination, the soil temperature may still influence the development of the young plant: Pehlivanurk (1976) found that time from emergence, after adequate moisture was present, to crown root development and tillering increased considerably after soil temperatures dropped below a certain range.

In many summer crops, like maize and sorghum, meristemic tissue remains below ground for much of the vegetative growth period, so that soil temperatures are probably more important than air temperatures during early plant development.

As plants develop, air temperature and light gradually become of greater importance, but soil temperatures still influence plant growth.

Soil temperature affects the metabolism of the roots, and hence their ability to take up water, which in turn influences plant growth. In maize, e.g., when soil temperature drops below 28°C, there is a decrease in leaf elongation rate due to restricted water uptake by the roots. When plant water potential reaches –9 bar, leaf elongation ceases due to the decline in turgor pressure (Barlow et al., 1977).

The soil temperature during the day is often of greater importance than at night, since it is necessary to maintain a favourable internal crop–water status in the presence of high evaporative demand during the day (Bierhuizen, 1973).

Soil temperature extremes can be considerably mitigated by mulching, by forming a loose upper layer by cultivation and by any practice that conserves water.

Moisture regime

As a result of the heating of the soil surface, which may be considerable in arid climates, a steep temperature gradient occurs, which may cause a considerable movement of water through the soil.

There is a continuous exchange of air between soil and atmosphere. When water penetrates into the soil, air is expelled; as the soil dries, fresh air is drawn into the soil. The air in the soil is usually moisture-saturated, excepting under conditions of extreme dryness.

Wet soils absorb more radiant energy than dry soils. Most of the energy is used for the evaporation of the soil water; as water is also a good conductor of heat, the remaining radiant energy will warm deeper soil layers. By contrast, the surface of dry soils, and the air layer above them, will be at higher temperatures than is the case with moist soil. Variations in temperature of a desert soil at a depth of 0.4 cm from 17.0°C in the early morning hours to 71.5°C at midday were recorded at Tucson, Arizona, USA. The maximum temperature was 21.1°C higher than at a depth of two centimetres in the soil.

In research carried out at the Laboratory of Climatology in the Great Plains region of the United States, it was found that, when a soil is at field capacity – i.e., holding all the water it can without being waterlogged – 80–85% of the incoming energy was used for evapotranspiration; as soil moisture was depleted, this proportion decreased.

In arid regions, as a result of the low moisture content of the soil and the sparse vegetation, actual evapotranspiration is low and most of the incoming radiation serves to heat the soil and the air above it. When the surface of a moist soil is covered by vegetation, the amount of evapotranspiration is determined mainly by the amount of incoming radiation, and is otherwise mainly affected by differences in albedo between different plant covers. However, as the soil dries, the ability of different types of vegetation to use soil moisture will make itself felt, and thereby affect actual evapotranspiration.

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CHAPTER 3

Soils of the Dry Zones

Soil-forming processes in drylands

The principal factors of soil formation are the nature of the parent material, climatic conditions, vegetation, soil organisms, and relief – all of which interact with one another, thereby intensifying or mitigating the effects of each individual factor.

The soil-forming processes, under the combined effects of climatic and biological factors, proceed in a number of well-defined stages until the soil reaches ‘maturity’ – at which stage it is more or less in equilibrium with its environment.

Parent material

The mineral content of arid soils depends mainly on the nature of the parent rock.

In the dry regions, many soils are formed over parent materials with a high proportion of CaCO_3 . These soils tend to have a pH above 7. However, in the course of time, even with low rainfall, the Ca^{2+} ions tend to be leached out, gradually reducing the pH. Because of the high CaCO_3 content, these soils are well buffered, and the pH rarely falls below 5 (Fitter and Hay, 1987).

The influence of the parent material on soil characteristics is most apparent in young, imperfectly developed soils.

However, as many rocks give rise to often essentially similar final products of disintegration and chemical change, though in different proportions, the influence of the parent material may become largely obliterated in mature soils by the various soil-forming processes.

Climate

Though the nature of the parent rock has some influence on soil properties, climatic factors tend to have a greater influence in this respect, especially on soil properties of agricultural significance. This is borne out by the fact that mature soils which have developed in different regions but under similar climatic conditions, have certain

common characteristics, which are modified only by the nature of the parent rock and other specific local conditions such as slope, run-off, drainage, etc.

The soil-forming factors in the dry regions of the world are essentially the same as those influencing soil formation in more humid regions; their relative intensities are, however, different, and the soils formed are characteristic of the arid regions (Buol, 1965). In arid climates, physical weathering processes predominate whilst the chemical weathering processes, that are very effective in humid climates, can operate effectively only during the relatively short periods during which the soils are wet. The most important processes of soil formation in arid regions are therefore erosion and redeposition, together with restricted leaching of soluble materials and their redistribution. Clay formation, organic matter production, oxidation and reduction, etc., are processes of lesser importance.

The two main climatic factors influencing soil formation are rainfall and temperature, while winds can be important.

Rainfall

Water is essential for all the processes involved in chemical weathering of the parent rock: hydrolysis, hydration, solution, leaching, eluviation, oxidation, and carbonation. When the soil dries, dehydration also has important effects.

The alternate wetting and drying of the parent materials, which is particularly marked in the arid regions, also contributes to physical weathering – as a result of the stresses and strains that occur with each cycle of wetting and drying. The limited precipitation and rapid evaporation characterizing the arid regions, limit the depth of penetration of the rain, and result in long periods during which most of the soil is dry. Soluble materials are carried downwards in solution, and solid particles by eluviation, to the depth of penetration of the water. This depth depends on the nature of the soil, especially its texture, and on the amount and intensity of rainfall. It is only very rarely that the entire soil profile is leached. As a result, soluble salts and calcium carbonate accumulate at a relatively shallow depth; the carbonates frequently form a hard-pan, called ‘caliche’, that is typical of many soils in the dry regions. Silica may contribute to the cementation of soil layers. The calcium carbonate may also appear as soft or hard nodules in the calcic horizon. A continuous process of soil erosion may expose this calcium layer, which is then called petrocalcic horizon. These calcium crusts cover large areas of arid and semiarid soils (Dan, 1977).

The subsoil of many soils in the dry regions shows a higher *clay content* than the topsoil (Buol, 1965). It is assumed that conditions are more favourable for clay formation in the subsoil, because it is moist for longer periods than is the topsoil. Notwithstanding the low rate of clay formation in arid regions, many of the soils are rich in clay (Kelley, 1951). Clay concentration in the B horizon is also enhanced due to the occurrence of sodium cations.

In the semi-arid regions, on the fringes of the deserts, precipitation is more plentiful, moisture penetrates more deeply, and it is retained for longer periods. This makes

a better-developed vegetative cover possible. The soils of these regions, especially in the cooler, temperate semi-arid lands, are therefore characterized by a dark-coloured topsoil, with a relatively high content of organic matter, and a subsoil that is rich in soluble elements and in calcium.

The soil profile. As a result of the leaching, etc. processes described above, it is accepted practice to distinguish between a number of horizons of the soil profile:

- A: is the eluvial horizon from which material has been leached out;
- B: is the illuvial horizon in which the clay carried down from A has accumulated;
and
- C: represents the disintegrated but less-weathered parent material.

Concentrations of carbonates, sulphates, and soluble salts, may be found in the master B horizon (and indicated as Bca, Bcs, and Bsa, respectively) or in the C horizon (indicated as Cca, Ccs, and Csa, respectively).

Temperature

The intense heating during the day and rapid cooling at night, that are characteristic of arid regions, are conducive to alternating expansion and contraction of the parent rock which cause cracking of the rocks and the flaking off of rock fragments; however, the importance of this process appears to have been overestimated (Hills et al., 1966).

High temperatures also intensify the chemical weathering processes in the relatively short periods during which the soils are moist, the speed of chemical reactions doubling, approximately, with every increase of 10°C in temperature.

Winds

Winds intensify the drying effects of aridity and promote erosion. The sparser the vegetation, the greater the erosive power of the wind. In the desert and semi-arid regions, the high-velocity winds carry sand particles and cause a considerable amount of abrasion and scouring of rock surfaces. They also transport and finally deposit loess and sands.

Biological soil-forming agents

The effect of vegetation on soil formation is relatively complex, because it is linked with ecological succession. At any stage in the soil-forming process, the vegetation both reflects contemporary soil conditions and influences the future course of soil development (Fitter and Hay, 1987). Vegetation generally plays a far less important role in the soil formation processes of desert soils than in those of the semi-arid regions.

Soils in the dry regions are characterized by a low content of organic matter, as a

result of the sparse vegetation producing but little residue. The organic matter content of some desert soils may be much less than 1%.

The high temperatures favour the predominance of oxidizing processes, resulting in limited formation of humic acids (Marbut, 1929). The C/N ratio is relatively low, possibly as a result of the activity of nitrogen-fixing blue-green algae, which are frequently present on the soil surface. Nitrifying bacteria have also been shown to be active in relatively dry soils (see Ch. 10).

When the soil is poor in calcium and contains sodic alkali, the humus is dispersed, producing the typical black colour of these soils. While the typical soil fauna of humid soils, especially earthworms, are commonly absent from desert soils, many other animals burrow in the soil to protect themselves from the hot sun and dryness during the day, and thereby have some influence on soil characteristics.

Relief

Relief affects soil formation by influencing run-off, erosion, sedimentation, and drainage. The run-off from slopes may collect in depressions, creating relatively humid 'micro-regions' which result in the formation, very locally, of soils that are characteristic of regions of higher rainfall.

There exists a close relationship among the factors affecting soil formation – especially relief, climate, and soil cover. In the extremely arid areas, the lack of plant cover favours the removal by wind or water of the fine soil particles, which can be redeposited only in closed basins. In somewhat less arid conditions, the ecological environment in depressions or on the cooler slopes may enable development of a dense vegetation cover that is sufficient to collect and hold fine eroded particles. With increasing precipitation and on approach to semi-arid conditions, most of the area that is of a moderate relief will be covered with fine soil.

Systems of soil classification

Review

Importance

Transfer of technological innovations occurs mostly by transfer of knowledge and experience from one region to another. Successful transfer and the avoidance of failures involves a careful comparison, not only of the climatic factors, but to an equal degree of soil characteristics of the regions involved. Hence the importance of classifying soils according to their natural relationships which indicate their major characteristics and production potential, information that is also essential for development planners. Soil surveys can indicate potential constraints as well as benefits, and how the soils respond to different management practices.

Irrigation projects in particular, require the information provided by soil taxonomy. Through comparison with similar soils which have already been under irrigation for various periods of time, the long-term effects of irrigation can be predicted, and mistakes in planning averted.

New systems

Until the 1970's, soil classifications were almost entirely made for single countries or groups of countries, and related to the specific soil characteristics of the areas involved. Even in comprehensive world taxonomy systems, such as the pioneer Russian soil classification system, and the old American system, the approach was biased by the particular national interests of the soil scientists involved in developing the respective systems.

In view of the large number of existing classifications, the nomenclature that did not always correspond to similar soil types and the frequently encountered inaccuracies in the description of the soil types, a number of new systems have been developed. The two systems that are most widely recognized and used are the American Comprehensive Soil Classification System and the FAO/UNESCO World Map.

The American Comprehensive Soil Classification System

The new system has been prepared by the soil survey staff of the USDA Soil Conservation Service, after a 20-year effort (Soil Survey Staff, 1975). It replaces the older system which comprised three orders: zonal soils, intrazonal soils and azonal soils.

The new system is flexible and "consists of classes that can be grouped or subdivided and regrouped for the most effective kinds of interpretations of responses to soil treatments and management systems" (Johnson, 1980). It is also the only major soil classification system that directly uses soil moisture regimes and temperature values to differentiate between classes. Kimble et al. (1988) stress that this is a major innovation in soil taxonomy, because it recognizes that water is one of the major controls in soil-forming processes, and that the actual soil moisture regime varies according to soil type and its location (slope), even under similar atmospheric climate. Furthermore, crop performance is more a function of soil moisture regime than of total precipitation.

The American system is considered to be a precise tool for describing, classifying, and comparing soils from around the world. Its major drawbacks are: (a) the need for specialized knowledge and experience in using the method; (b) it requires, in some cases, data which cannot be obtained within a reasonable time (Vink, 1975).

In the American system there are six taxonomic levels of classification: order, suborder, great group, subgroup, family and series. Because the soils within each level become more similar, technology transfer on the basis of taxonomic information becomes more reliable as one descends through the levels from order to series. It is only in relatively homogeneous orders and suborders, such as Vertisols, Histosols

and Andepts, that useful interpretations can be made at the highest levels (Swindale, 1989).

The Soil Map of the World

The Soil Map of the World (UNESCO, 1979, revised in 1985) is a joint project of FAO, UNESCO, and the International Society of Soil Science. Among the objectives set for the Soil Map were: (a) to make a first appraisal of the world's soil resources; (b) supply a scientific basis for transfer of technologies between similar environments; and (c) establish a generally accepted soil classification and nomenclature (FAO-UNESCO, 1985).

Subsequently, the Soil Map of the World served as a basis for policies of development: a world map of desertification, a study of potential population-supporting capacity of lands, and a delineation of similar agro-ecological zones in the world, were some of the major undertakings for which the World Soil Map served as a basis.

Soil classification in the World Map has been based to a large extent on the same criteria used in the American system, but the names given to similar orders are different, a possible source of confusion. Thus, at least one objective of the Soil Map of the World, i.e., "to promote a generally accepted soil classification and nomenclature" was not achieved.

Because of the small scale of the Soil Map of the World (1 : 5 000 000), the soils are classified at only two levels, whilst six to seven levels are required for more detailed maps. However, a number of individual countries have prepared national soil maps using the Soil Map of the World legend, eventually introducing third-level soil sub-units.

Elements of the American approach, as well as of other systems (see below), have been incorporated and have thereby contributed to its usefulness for classifying soils for practical purposes (Vink, 1975).

One of the general principles adopted for the preparation of the World Map was that no climatic criteria would be used to define the soil units. However, in the light of experience, an exception was made for soils that occur dominantly under arid and semi-arid conditions. Henceforth, the soils of arid regions will be separated from morphologically similar soils in other climatic environments by delineation on the soil map of the boundaries of arid climatic zones (FAO-UNESCO, 1985).

Nomenclature

The use of generally accepted soil names is a necessity. "Such names are meant to sum up, in an easily remembered term, a set of characteristics which have been found to be representative of a particular soil in different parts of the world" (FAO-UNESCO, 1985).

The policy of the Soil Map of the World has been to make use, as far as possible, of existing soil names which had acquired international status. However, certain names used previously could not be retained because of the confusion resulting from

dissimilar use of these terms in different countries, and new names were coined. Names no longer in use include such familiar terms as Brown Forest, Prairie, Mediterranean, Desert, Semi-arid Brown, and Alluvial soils.

By contrast, the American Soil Classification System has deliberately avoided the use of terms already in use, and has replaced them by an artificial, modular nomenclature, in which the names of soil units comprise formative elements, generally derived from Greek or Latin, and related to specific properties.

For workers familiar with the nomenclature used in the traditional soil classification system, the move from the well-known Solonetz, Solonchaks, Podzols, Cher-

TABLE 3.1

Orders and comparable soil groups

Soil orders of the US Comprehensive Soil Classification System	Comparable soil groups of the Soil Map of the World	Approximate old US classification
Entisols (ent=recent) (common in arid lands)	Fluvisols, Regosols, Lithosols, Arenosols, Rankers	Alluvial, Regosols, some Low-Humic Gleys
Inceptisols (ept=inception) (occur in semi-arid zones)	Gleysols, Andosols, Cambisols	Brown Forest, Andosols, some Low-Humic and Humic Gleys
Alfisols (alf=pedalfer) (occur in semi-arid zones)	Solonetz, Luvisols, Podsoluvisols, Planosols Acrisols, Nitosols	Half-Bog, Grey-Brown Podzolic, Planosols, Non-calcic Brown
Ultisols (ult=ultimate) (rare in dry areas)	Acrisols with low base saturation	Reddish-Brown Lateritic, Red-Yellow Podzolic
Spodosols (od=spodos) (not found in dry regions)	Podzols	Podzols, Podzolic, Groundwater Podsol
Oxisols (ox=oxide) (occur occasionally in arid lands)	Ferralsols	Laterite
Aridisols (id=dry) (extensive in arid lands, and some semi-arid regions)	Solonchaks, Solonetz, Yermosols, Xerosols	(Reddish) Brown, (Red) Desert, Solonchaks, Sierozems
Vertisols (ert=invert) (occur in arid and semi-arid lands)	Vertisols	Tropical Black Clays, Grumosols, Regurs, Tirs, Black Cotton
Mollisols (oil=mollify) (rare in dry regions)	Rendzinas, Kastanozems, Phaeozems, Greyzems, Chernozems	(Reddish) Brown, Brunizems, Chernozems, (Reddish) Chestnut, (Reddish) Prairie, Rendzinas, Humic-Gley
Histosols (ist=histos)	Histosols	Bog soils

nozems, Serozems, etc., to the, at first sight, cumbersome and complicated new nomenclature of the American System may well be bewildering. "The artificiality of the nomenclature and the nearly abandonment of previously used names brought about considerable resistance to the new system, in early years, but its merits outweighed the objections, with the result that the system is now accepted widely" (Dregne, 1976).

The recent literature on a wide range of agricultural topics uses the new nomenclature when referring to soils; the non-specialist who requires up-to-date information on soils, has no choice but to familiarize himself with at least one of the new systems. Here, we will relate in detail only to the new US Soil Taxonomy, but in order to facilitate the transition to new concepts and terminology, Table 3.1 summarizing the main characteristics of the soil orders of the new US Soil Taxonomy, also gives the roughly equivalent names of comparable soil groups of the FAO-UNESCO Soil Map of the World, as well as those of the previous US system. The reader will also find useful a list of the formative elements used in the names adopted by the US Taxonomy (p. 117).

The US Comprehensive Soil Classification System

Organization

The new American system is *taxonomic*, i.e., soils are classified on the basis of their properties, and genesis is relevant only indirectly, through the selection and definition of the differentiating properties which result from soil genesis as well as properties that effect soil use.

These properties include soil moisture and temperature, thickness of horizons, organic matter content, mineralogy, exchangeable base status, colour, and other properties. Quantitative limits have been established for each property involved in the classification (Dregne, 1976).

By contrast, the earlier US classification system, as well as the Russian, French and Australian systems, are either based on *soil-genesis* processes, e.g., the influence of climate and vegetation on soil development, or a combination of genetic and taxonomic factors (Dregne, 1976).

Soil orders in relation to drylands

In the Comprehensive Soil Classification System (Soil Taxonomy) developed by the USDA Soil Survey Staff (1975), ten major orders are defined. Soils in a given order have similar morphology and have often been formed under similar circumstances (Hassett, 1979). Seven of these orders occur in the dry zones of world.

The ten orders, and the comparable soil groups of the Soil Map of the World are shown in Table 3.1.

It should be noted that, in general, there is no direct correspondence between the

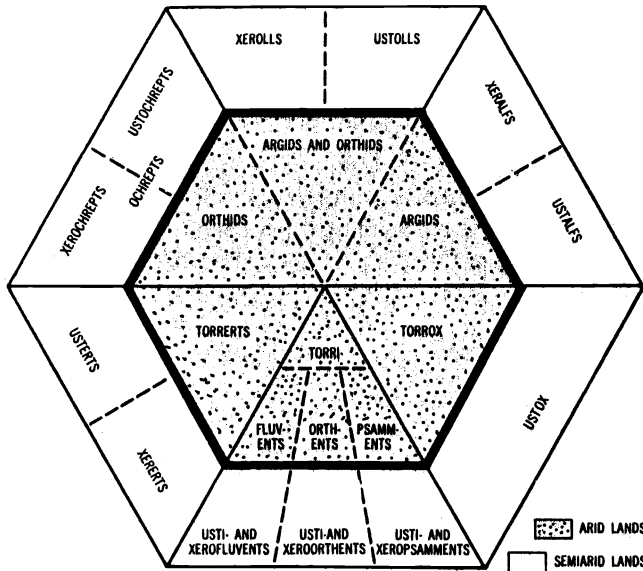


Fig. 3.1. Relationships among suborders and great groups of arid-land and semi-arid-land soils. From Flach and Smith (1969). (By permission of University of Arizona Press, © 1969).

orders of the US Soil Taxonomy and the soil map units of the UNESCO World Soil Map.

Classification within orders

Suborders (Fig. 3.1). In the US Soil Taxonomy, soil water and temperature are considered as soil properties; the classification within orders is usually on the basis of climatic and associated factors, of which the most important is generally the soil water regime (SWR) under which the soils were formed.

The development of the Entisols (as well as that of the Inceptisols (see below) was more influenced by the nature of the parent material, topography, and other factors than by climate. Therefore, the distinctions between suborders in these two orders are not based on moisture regimes.

The name of each suborder consists of two syllables: the first reflects a property, the second indicates the order. For example, Ustalfs are a suborder of *Alfisols* formed under an *Ustic* regime (see below).

Great groups. Within each suborder are great groups, defined largely according to the presence of diagnostic horizons and their arrangement. They also have in common their moisture and temperature regimes, and their base status.

The names of the great groups are formed by adding one or more formative

elements to the name of the relevant suborder. For example, Natrustalfs are a great group within the suborder Ustalfs, characterized by the presence of a natric horizon.

The subgroups. The subgroups are either transitional forms, or have some characteristics that are not representative of the great group to which they belong.

Subgroup names consist of one or more connotative adjectives placed before the great group name. A Typic Natrargid is a Natrargid with properties typical of the characteristics of the Natrargid great group; a Borollic Natrargid is a Natrargid that has some properties resembling those of the Boroll suborder.

Family. The family names contain the name of the subgroup, followed by one or more adjectives specifying properties relevant to the use and management of soils (texture, mineralogy, pH, soil temperature, soil depth, soil slope, soil-consistence classes, and others). A Typic Natrargid, fine, montmorillonitic, thermic, e.g., is a Typic Natrargid with a clayey texture, the clay being mainly of the montmorillonitic group, and having a hot thermic regime.

Series. This is the lowest category; the soil series names have no connotative value, and are based, as in the past, on the name of the locality in which the series was first described. This departure from the nomenclature system used for the other categories was necessary because connotative names for the series would be so long as to be excessively cumbersome to use (Dregne, 1976).

Diagnostic horizons (USDA-AID, 1985; EUROCONSULT, 1989)

The new US Soil Taxonomy makes use of diagnostic surface and subsurface horizons for the identification of soil classes.

Surface horizons (epipedons). Epipedons include the upper part of the soil that is darkened by organic matter. Six diagnostic epipedons are recognized, but only two are important for the classification of dryland soils (Flach and Smith, 1969): the *mollic epipedon*: a thick, soft, dark-coloured layer with good structure; Ca^{2+} is the dominant cation; and the *ochric epipedon*: light-coloured, low in organic matter, or thin.

Only a few soils of the arid lands have surface horizons containing enough organic matter to be mollic epipedons; these are however found in many soils of the semi-arid regions.

Mollic and ochric epipedons are basic to the differentiation of Aridisols from Mollisols.

Diagnostic subsurface horizons. Subsurface horizons normally occur under the epipedon. Some diagnostic subsurface horizons are not found in arid land soils.

Most soils with stable surfaces in the drylands have a B horizon from which some carbonates have been removed, the structure of the parent material has been altered,

some soil structure has formed, or some reddening has occurred (Flach and Smith, 1969).

The main features of the diagnostic horizons and subsurface horizons are shown in Table 3.2.

Diagnostic horizons are not mutually exclusive entities. For example, a mollic epipedon may contain an argillic subsurface horizon; plinthite may be found in ochric epipedons or in argillic horizons (Dregne, 1976).

TABLE 3.2

Diagnostic horizons and features

Diagnostic horizons	Pedologic significance	Elements of definition ^a
Surface horizons		
mollic epipedon	surface horizon of accumulation of dark coloured organic matter and of plant nutrients, primarily in a grassland environment	dark colour, moist, value and chroma of 3 or less ^b ; thickness more than 25 cm; more than 1% organic matter; more than 50% base saturation; not hard and massive when dry
ochric epipedon	surface horizon with little organic matter accumulation	higher value or chroma of 4 or more, or lower organic matter content, or lower base saturation
Subsurface horizons		
argillic	horizon of clay accumulation	one-fifth more clay than the overlying horizon; coatings of illuviated clay on surfaces of structural units, sand grains, or in pores
natric	horizon of clay and sodium accumulation	same as argillic horizon and more than 15% exchangeable sodium
cambic	horizon of pedogenic alteration	evidence of soil structure (as contrasted to rock structure) or evidence of removal of calcium carbonate, or mottling
calcic	horizon of pronounced carbonate accumulation	evidence of pedogenic carbonates, more than 15% carbonate equivalent, and more than 15 cm thick
gypsic	horizon of pronounced gypsum accumulation	product of percent gypsum $\times$ thickness (cm) is 150 or more
salic	horizon of pronounced salt accumulation	more than 2% salt; thickness (cm) $\times$ percent salt is more than 60
duripan	cementation by silica and carbonates	opal or chalcedony coatings; does not slake completely in acid or water
petrocalcic	horizon indurated by pedogenic carbonates	containing as much calcium carbonate as the calcic horizon and indurated; does not slake in water but slakes completely in acid
Usually dry	dry for more than half of growing season	water at more than -15 bar tension, for more than half of the time the soil is warmer than 8°C

TABLE 3.2 (*continued*)

Other features	Pedologic significance	Elements of definition
Moisture control section	root zone of annual crops below zone that dries rapidly	zone not moistened by a 2.5 cm rain, but moistened by a 7.5 cm rain
Durinodes	silica cemented nodules	weakly cemented nodules with concentric stringers of opal
Lithic contact	lower limit of the soil over hard bedrock	as hard or harder than 3 on the Mohs scale
Paralithic contact	lower limit of soil over soft rock	less hard than 3 on the Mohs scale but can be dug with a spade only with difficulty
Slickensides	evidence of churning	shiny, intersecting, and striated surfaces

^aGreatly simplified. ^bMunsell notation.

From Flach and Smith (1969). By permission of the University of Arizona Press, Tucson.

Soil moisture regimes

Suborder, great group, and subgroup names frequently include formative elements (aqu, torr, ust, ud, xer) or adjectives (aquic, aridic or torric, ustic, udic, xeric) indicating soil moisture regimes.

For classification purposes, the *moisture control section* is that part of the root zone of annual crops that is below the soil layer that dries rapidly; the upper limit of the section is that wetted by 25 mm of water within 24 hours; and the lower limit that which is wetted by 75 mm of water within 48 hours.

The five moisture regimes are (USA-AID, 1985):

The Aridic and Torric regimes: the terms Aridic and Torric are used for the same moisture regime, but in different catagories of the Taxonomy. The moisture control section is dry for more than half of the growing season and never moist in some or all parts for as long as 90 consecutive days, when soil temperature at a depth of 50 cm is above 8°C. There is very little or no leaching in these regimes, and soluble salts accumulate in the soil if a source is present.

Soils that have an Aridic (Torric) regime are generally predominant in arid regions. A few are in semi-arid areas, when their dryness is due to physical characteristics that prevents infiltration of water, such as soil crusts, or are very shallow over bedrock.

The Xeric regime (Gr. Xeros, dry): characterizes the soils of the regions with a Mediterranean climate, e.g. with winter rainfall and warm, dry summers. The moisture control section, in part or entirely, is dry for 45 or more consecutive days within the four months that follow the summer solstice in six or more years out of ten.

The Ustic regime (L. ustus, burnt): characterizes soils of the semi-arid tropics, and is intermediate between the Udic and the Aridic regimes. It is typified in a monsoon climate that has at least one rainy season of three months or more. Soil moisture is

limited, but is present at a time when temperature conditions are suitable for plant growth.

The Aquic regime: prevails where the soil is saturated by ground water or by water of the capillary fringe, and therefore implies a reducing regime that is virtually free of dissolved oxygen.

The Udic regime (L. udus, humid) is characteristic of humid regions, with a well-distributed precipitation, which exceeds PET during most months of the year.

Soil temperature classes

Knowledge of soil temperature permits several inferences to be made about the chemical, biological, and, occasionally, physical characteristics of the soil (Dregne, 1976). Six soil temperature classes are used in the US Taxonomy: *pergelic* ($<0^{\circ}\text{C}$), *cryic* ($0\text{--}8^{\circ}\text{C}$), *frigid* ($<8^{\circ}\text{C}$), *mesic* ($8\text{--}15^{\circ}\text{C}$), *thermic* ($15\text{--}22^{\circ}\text{C}$), and *hyperthermic* ($>22^{\circ}$). (The figures between brackets indicate mean annual soil temperatures at 50 cm.)

Major soils of the dry regions

Several soil–geomorphological associations distinguish the dry from the humid regions, as well as certain chemical properties. Aridity is naturally the controlling factor, but age of landscape, type of parent rock, distribution and intensity of rainfall, and the effect of man's intervention modify the effects of aridity (Dregne, 1976).

The major characteristics of dryland soils are: a generally low level of organic matter (the drier the moisture regime the less organic matter in the soil); alkaline to slightly acid reaction in the surface; calcium carbonate accumulation somewhere in the upper 150 cm of the soil; weak to moderate profile development, coarse to medium texture, and low biological activity (Dregne, 1976).

When average annual precipitation is less than 250 mm, in both low- and middle-latitude climates, soils generally have neutral to alkaline reactions, a base saturation of 90% or more, contain less than 2% organic matter, have a calcareous horizon within the top 2 m of soil, are at least slightly saline, and have a mineral clay complex dominated by illite and montmorillonite. When annual precipitation exceeds 250 mm, differences appear that are a function of rainfall quantities and distribution patterns, position on slopes, and age of soil (Dregne, 1976).

Entisols form the most common soil order in the dry regions, followed by Aridisols, Mollisols, Alfisols and Vertisols. The Aridisol order is the only one confined, by definition, to the arid regions. In extremely arid climates, only Aridisols and Entisols cover a region of significant extent (Dregne, 1976).

Entisols

Entisols are mineral soils that have only the beginnings of stratification; without



Fig. 3.2. Profile of a typical Entisol. Photo J. Dan.

clearly developed horizons (Fig. 3.2). They are found on recently formed or exposed parent materials, or those very resistant to soil development, such as sand dunes (Hassett, 1979). They are generally found in strongly eroded areas, in areas in which sediments were deposited rapidly and in desert areas.

These are the soils which were formerly defined as azonal, e.g., they are found in all climatic zones, but are especially characteristic for the very arid and arid zones.

Entisols may have any temperature or moisture regime except the combination of very low temperatures and wetness. The major suborders are defined according to the location of the soils and the nature of the parent rock:

Orthents include young soils submitted to severe erosion which prevents their maturing. They are usually found on steep mountain slopes and in deserts. The US Classification distinguishes between the Lithic subgroups (formerly defined as Lithosols) derived from hard parent rock, and various subgroups derived from friable parent rock (formerly known as Regosols).

The *Lithic soils* have an (A)C profile and are weakly developed, shallow, mineral, generally stony, and merge into or rest upon consolidated rock or rock debris (FAO,



Fig. 3.3. Desert pavement. Photo N. Tadmor.

1964). The soils of this group cover about 21% of the world's land surface, but account for only 2.5% of the arable land. They are usually too shallow or stony for crop production. Occasionally, they may have some agricultural potential; in North Africa they are used for growing vines and in South Africa for extensive grazing (D'Hoore, 1964).

The *Reg* soils also have an (A)C profile in which the (A) horizon is weakly developed. They differ from Lithosols in that they are formed from unconsolidated or soft materials that are predominantly mineral but not stony (FAO, 1964). Unlike the Lithosols, they are deep soils with uniform soil characteristics from the surface downwards to a depth of 150 cm or more. Most of these soils are sands.

The most widespread landscapes of *Reg* soils (generally included in Gypsiorthids) are gravelly desert plains covered by a *desert pavement* (Fig. 3.3) (*reg*, *hamada*, *gobi*) which consists of a layer of gravel, pebbles, or stones lying on top of the soil, which protects the underlying soil from wind and water erosion, and also reduces moisture losses. Organic matter content is very low.

Torriorthents are usually gravelly, of variable depth, but are deep when found in saline areas; they are slightly to moderately calcareous. Shallow Lithic *Torriorthents* are found in the mountainous areas of the arid zones.



Fig. 3.4. Shifting dunes in the Negev Desert. In the foreground, *Aristida scoparia* establishing a foothold; in the distant background, dense vegetation of *Artemisia monosperma* on arrested sand fields. Photo N. Tadmor.

Psammments include all soils with more than 95% sand, and leached sandy soils, such as very sandy Podzols. They may occur under any climate, and on surfaces of any age. Included in the *Psammments* are shifting and stabilized sand dunes, cover sands, and sand fields (Fig. 3.4). Wind erosion is a major hazard.

Wide expanses of *Torripsammments*, very deep and relatively stabilized sandy soils are encountered in arid areas.

The *sandy soils* of the arid regions have certain common characteristics because of the sparse vegetation, the dryness, and the absence of clay particles; the components



Fig. 3.5. Not all desert areas are dry! Surface of a wet 'playa' (Salorthid). Photo J. Dan.

of these sandy soils are easily moved by wind to form shifting sand dunes, which are a characteristic component of the landscape of these regions. Some dune areas form vast 'seas' of sand, examples of which are the *ergs* of North Africa, the Rub al Khali of Saudi Arabia, and the Takla Makan Desert of China (Fig. 3.5).

For desert vegetation, the best soils are undoubtedly the sandy soils, and the most favourable sites are along the lower, gentle slopes of dunes (Bagnold, 1954). With their high permeability, sandy soils rapidly absorb rainfall even from relatively light precipitation, and run-off is minimal even after heavy storms. At a depth of 20 to 30 cm, water may remain to form a moist if unsaturated zone between dry layers of sand, both above and below, for extremely protracted periods.

It has long been recognized that sandy soils, when irrigated, frequently form the most productive oases of the North African deserts (Hilgard, 1930). Their productivity may remain unimpaired even after long periods of irrigation with relatively saline water.

Aquents include undeveloped poorly drained soils. *Fluvaquents* (formerly known as hydromorphic soils) are Entisols encountered in wet locations in arid zones, and are relatively rich in organic matter.

Another characteristic feature of the arid region soils is the presence of *playas* (Fig. 3.6): broad, shallow depressions in the landscape, from which only rarely a surface outflow of water occurs. The deposits consist of a fine, silty alluvium, that may contain various amounts of calcium. Called *takyrs* in the Soviet Union, they generally have a non-saline surface because of occasional leaching by floodwaters, and a light to moderate saline subsoil.

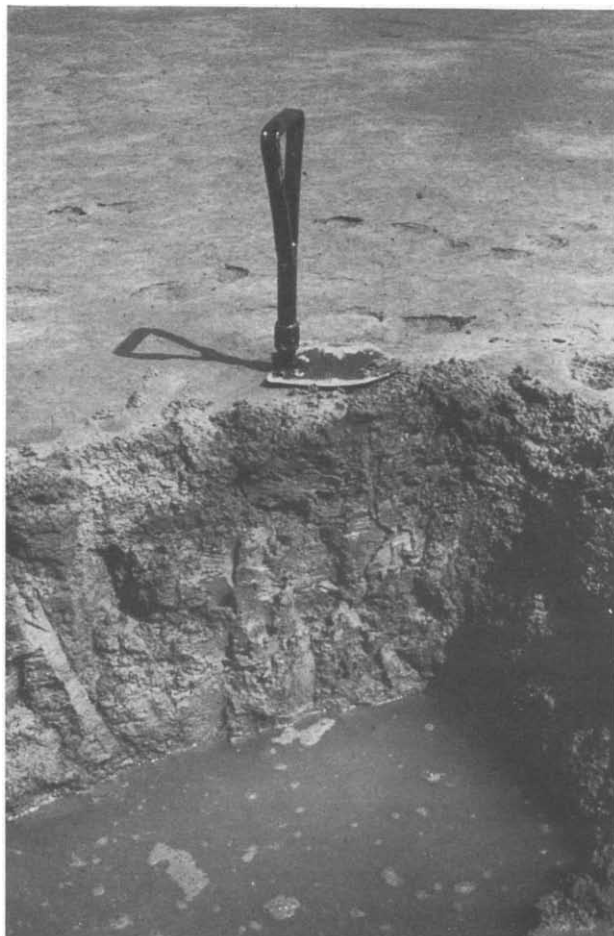


Fig. 3.6. Profile of a sterile Salorthid found in the centre of a wet playa in which the high salinity inhibits plant growth. Note high water table. Photo J. Dan.

Fluvents include all soils formerly classified as alluvial soils, i.e. young soils formed from eroded sediments deposited in flood plains, alluvial fans, desert river beds, and in areas in which soil stratification resulted from water flow. The texture of these soils ranges from very coarse (stones and sand) to very fine clays (Dan, 1985).

Within the reg areas are wide floodplains which generally comprise alluvial soils (Torrifluvents).

Alluvial soils (formerly included in the Intrazonal soils) have certain common characteristics: they have been formed on recent deposits of fluvial, marine, or lacustrine origin. The A horizon, when present, is weakly developed and merges into undifferentiated, wet, mineral material that constitutes the C horizon and often shows evi-

dence of reduction (gley). The total thickness and organic matter content vary sharply with drainage and climate (FAO, 1964).

Alluvial soils occur on bottom lands, floodplains, and low terraces along streams, the term 'alluvial' applying to recently deposited water-laid materials which have been little affected by the local environment. Their characteristics are determined by the nature of the parent materials, and the manner in which they have been transported, sorted, and deposited.

Alluvial soils are characteristic of the principal irrigated areas of the world, such as the Nile Valley, the basins of the Tigris and Euphrates, the basin of the Indus and its tributaries, etc.

The fertility of alluvial soils depends on their origin: if they developed from poor rocks or from laterite, their fertility will be extremely low; if they developed from the erosion of nutrient-rich soils and rocks such as limestone and basalt, they can be very fertile (Kellogg, 1953).

Aridisols

Aridisols are soils with an arid moisture regime, that have an ochric epipedon and one or more of the following horizons: argillic, natric, cambic, calcic, gypsic, salic, duripans (EUROCONSULT, 1989).

Aridisols have a restricted development due to dryness of the climate; leaching is minimal and accumulations of soluble salts (salic), gypsum (gypsic), or calcium carbonate (calcic) are frequent.

These soils are found in most of the deserts and near-deserts of the world. The moisture regime is arid or torrid. The soils are usually deep, have low organic content, and support sparse vegetation, except in depressions. A common characteristic of upland Aridisols is a desert pavement (cf. p. 99), the result of the removal of the fine material by water or wind, leaving the large-sized soil components on the surface.

Because these soils are only found in dry climates, distinctions between suborders are based on whether they have argillic or natric B horizons.

Argids have an argillic or natric horizon, in which silicate clays have accumulated by illuviation from upper horizons (much of the illuviation may have occurred in former pluvial periods). They may have a calcic or petrocalcic horizon or a duripan.

Orthids do not have an argillic or natric horizon. In general, they have developed on younger materials than the Argids, and are probably the product of the present climate, excepting petrocalcic Orthids.

Various grey, brown and reddish soils (*Argids* and *Orthids*, among them also *Palaeargids* and *Paleorthids* which contain a petrocalcic horizon) cover the plains, pediments, footslopes and inactive alluvial fans. These have a typical AB_{ca}C or ABC_{ca} horizon sequence.

Most of these soils have more or less high concentrations of adsorbed sodium, identified by the prefix Natr, Natri or Natru (e.g. Natrargids).

In the Soil Taxonomy, the formerly called *Solonetz* soils are included within the Natric great group of Aridisols. These soils occur extensively in semi-arid and subhumid grassland areas. They develop where high levels of sodium are maintained within the solum. The B horizons have dense clayey soils, with high soluble and exchangeable Na contents, and are slowly permeable to air and water. Root growth is generally limited to the A horizon, making crops very susceptible to moisture and nutrient stress and resulting in low crop productivity. A balance between downward leaching of soluble Na and capillary rise must be maintained to preserve the natric B horizon. Slight changes in climate or soil management which enhance downward leaching result in the removal of Na from the B horizon (Boehm et al., 1988).

Similar to the *takyrs* in physiography, but different in the salinity of the soils are the saline depressions encountered nearly everywhere in arid regions, whether hot or cold. Owing to their wide distribution, they are known by many names: salinas, salares, sabhas, salt lakes, chotts, salt flats, etc. They are *Salorthids*, characterized by a surface crust of salt or salt efflorescences; they comprise the saline soils formerly known as *Solonchaks*. The major source of the salts is a high water table (Fig. 3.6).

The soils formerly named *Serozems* (Xerollic subgroups of Durargids, Haplargids, and Palargids) have an A horizon that is weakly developed, light greyish-brown or light-grey, vesicular, and weakly platy, with a low to moderate content of organic matter (less than 2%). The B horizon, if present, is finer textured than the A and has a prismatic structure.

These soils are commonly weakly calcareous in the surface horizons, become highly calcareous in depth, and the zone of lime accumulation may be present in the (B) while a gypsiferous zone is usually present in the subsoil. These soils occur in climates with cool to cold winters, and rainfall during the cool season. The soils are dry for most of the year and are only occasionally moistened throughout their depth (FAO, 1964).

Amongst other soils included in the Aridisols, are those with a pronounced gypsic horizon (*Gypsiorthids*), which are widespread in extremely arid zones.

In the Soil Taxonomy, Aridisols also include most soils of the arid zones, such as those formerly known as grey, red, and reddish grey desert soils (Dan, 1985).

Mollisols

Mollisols are found mainly in the semi-arid and subhumid grasslands, and have dark-coloured surfaces and high levels of bases such as Ca and Mg, with a mollic (well-structured) epipedon and a high level of base-saturated organic matter. Argillic, calcic, or natric horizons may be present. Moving from the drier to the more humid areas, the mollic horizon becomes progressively deeper and richer in organic matter. Mollisols may have any temperature or moisture regime that provides growing conditions enabling the development of perennial grasses.

In many mollisols, the B horizon is cambic or argillic. In the semi-arid areas, a Ca horizon is also frequently present, as the result of moderate leaching.

Ustolls are Mollisols of the summer rainfall semi-arid and humid areas. They are more or less freely drained and are not saturated with water at any period of the year. Their moisture regime is ustic or aridic, but never xeric (Dregne, 1976).

The Ustolls include the formerly named *Chestnut Soils* (Dan, 1985). The A horizon of these soils is relatively thick (30–50 cm) and granular, with a moderately high content of organic matter which is mull. The A horizon may grade into a dark-brown to reddish-brown B horizon with a prismatic structure and often showing evidence of clay movement. The base saturation is generally higher than 80%, while the ratio of bivalent to monovalent cations decreases with depth. The B horizon may overlie a horizon of lime accumulation which is often hardened, for these soils are moderately calcareous and the content of calcium carbonates increases in the lower horizons. The silicate clays are mainly of the illite group. Chestnut soils occur under semi-arid climates in which the soil is dry for several months of the year and is only occasionally moistened throughout its depth during the rainy season (FAO, 1964). They may also occur in areas of subhumid climate and so link up with the next category.

Borolls are more or less freely drained soils of cool to cold middle-latitude climates, and usually have an ustic moisture regime. In the semi-arid and subhumid steppes are found the formerly named *Chernozems*, black soils rich in organic matter, classified in the Soil Taxonomy as Haploborolls, Vermiborolls, Calciborolls, and Argiborolls, according to the nature of their respective A horizons (Dan, 1985). The A horizon generally shows a high degree of biological activity. It grades into the C or into a light-brown to brown (B) horizon. The (B) horizons are usually transitional layers between the A horizons, which are rich in organic matter, and the C horizons consisting almost entirely of parent material (Winters and Simonson, 1951).

Chernozems may be calcareous throughout or have a layer of lime accumulation of which the depth varies with the CaCO_3 content of the parent material and with climatic conditions. Chernozems have a high base saturation. They develop in temperate to cool, subhumid climates in which the soil is dry for several months of the year but may be moistened throughout its depth during the rainy season (FAO, 1964); their typical vegetation is grassland.

Xerolls are Mollisols formed under a Mediterranean climate (wet winters and dry summers), opposite to the climatic conditions under which Ustolls are formed. Xerolls have a xeric or aridic moisture regime.

Alfisols

Alfisols are a unique order in that they occur in two quite different environments: tropical semi-arid savannahs and temperate humid climates.

The Sudanian Sahel typifies the savannah Alfisol area. Alfisols are also one of the major soil types of the semi-arid tropics. They occur extensively in southern Asia,

western and central Africa and in many parts of South America, mainly northeast Brazil (Cochemé and Franquin, 1967).

Alfisols have a thin light-coloured surface horizon and highly developed argillic or natric subsurface horizons, which may restrict root penetration; the clay content increases with depth (El-Swaify et al., 1983). Shallow and gravelly Alfisols, resulting from erosion, are also common.

The degree of weathering of the parent materials is greater in the semi-arid tropics than in the drier areas; hence the level of plant nutrients is lower in the former.

At the suborder level, Alfisols are within the ustic moisture regime, e.g., dryness during part of the year and presence of moisture during the season suitable for plant growth (Soil Survey Staff, 1975). The ustic regime is typical for monsoon climates that have at least one rainy season lasting three months a year, or more.

Whilst the major suborder of the Alfisols in the subtropical and tropical semi-arid areas are Ustalfs, in the Mediterranean winter rainfall areas, it are mainly Xeralfs that are encountered (Dan, 1985).

Ustalfs have a moisture regime that is ustic, and a temperature regime at least as hot as thermic. Soil colour is usually reddish and drainage is good. A calcic horizon is sometimes found in or below the argillic horizon. The Ustalfs are found where the vegetation is grassland with scattered xerophytic trees, the growing season is long, protracted dry periods occur at times during the growing season, and the rainy period(s) is (are) short (Dregne, 1976).

Xeralfs have a xeric moisture regime; the soils are dry for extended periods during the summer, whilst they can be very wet during the winter months. Temperature regimes are usually thermic (Dregne, 1976).

Three great groups of Alfisols are of major agricultural importance in the semi-arid tropics. These are the Haplustalfs, Rhodoxeralfs and Paleustalfs (El-Swaify et al., 1983).

Haplustalfs have a sandy loam surface with low organic content. They are usually acidic, with a base saturation of about 50%. Near the surface, a sandy kaolinite loam or a sandy kaolinite are found, with high base saturation. Typical vegetation is savannah.

Rhodoxeralfs are a winter-rainfall soil group. The surface organic content is about 1%. The lower argillic layer has a base saturation of 60% or more. They generally support open woodland with shrubs and some grass. *Paleustalfs* are thicker and more acid soils than the two former groups.

The *Haploxeralfs* and *Rhodoxeralfs* comprise the formerly called *Red-Brown Mediterranean soils*. These include the non-calcic brown soils and are soils with an ABC profile. The A₁ horizon is well developed and has a moderately high organic-matter content which is mull; this horizon merges into a red or brown, angular-blocky B horizon. A weakly developed A₂ horizon may be present. The clays are of the illite and kaolin groups. The base saturation is higher than 35% and increases with depth. During the dry period of the year, the A and B horizons become hard and in some

soils hardpans have been reported to occur below the B horizon. The boundaries between the main horizons are distinct.

The Red–Brown Mediterranean soils range in depth from 40 to 100 cm or occasionally more. They occur in humid and subhumid climates with a marked dry season. The soil is dry for several months of the year but is moistened throughout its depth during the cool rainy season.

Aqualfs show evidence of poor drainage and have an aquic moisture regime, unless artificially drained. In Alfisols in which hardpans are present, there is a sharp transition from the coarse-textured A horizon to the sealed B horizon with gley characteristics; these soils are *Albaqualfs*.

Vertisols

Vertisols are the moderately deep to deep cracking clays of the warm regions. Clay content is at least 30% in all subsections of the profile down to 50 cm. These soils develop within climates that are warm to hot, with a seasonal rainfall that is both sufficiently high to moisten the soil in depth and sufficiently short to allow a strong desiccation in season (Blokhuys, 1989). These conditions are typical for the semi-arid tropics and subtropics. Comparing the semi-arid regions with the main Vertisol areas of the world, Beek et al. (1980) showed an overlap of about 70%. The major areas of Vertisols and associated soils are located in Australia, Sudan, Chad, India and Ethiopia. These five countries have over 80% of the total area (250 million ha) in the world (Virmani et al., 1989).

While the vertisols make up a relatively homogeneous order in a taxonomic sense, Dudal (1989) stresses the great diversity in characteristics that affect their wetting and drying, and therefore their suitability for crop production; hence the need to adjust management practices for different water storage capacities and soil depths, e.g.

In India, they receive 500 to 1300 mm of annual rainfall, concentrated in a short period of 90 of 105 days, interspersed with periods of drought and a growing season ranging from 147 to 231 days, in different years (Virmani et al., 1989).

The most important aspect of soil formation in Vertisols is the alternation of water uptake and swelling in the wet season, with shrinkage on drying in the dry season (Blokhuys, 1989).

Vertisols are heavy soils; their texture may be clay, clay loam, or silty clay loam; clay content generally ranges from 40 to 60%. The surface horizon is thick and, though dark in colour, relatively low in organic matter. The surface layer is generally granular when dry and sometimes develops a crust, whereas the lower part usually develops a prismatic structure.

The high clay content causes the soil to contract and expand with alternating wet and dry conditions. The cracks that develop can reach a depth of 50–150 cm. The surface soil breaks apart into fine granular or crumb aggregates, forming a surface

mulch. The small particles fall into the cracks, causing the surface layer to invert after several years. Light rains close the cracks at the surface; heavy rains fill the cracks and close them completely (Dudal, 1989).

The dominant clay mineral is smectite, of the montmorillonite series. Because of their high clay content and related physical properties, the Vertisols generally have high water-holding and ion-exchange capacity, but low permeability. Much water is held at wilting point, so that available moisture is limited.

In the Soil Taxonomy, *Hortisols* are included within the *Vertisols*; these are soils derived from basic parent rocks such as basalts, alluvial clay sediments, or aeolian deposits. They are mainly found in semi-arid to subhumid zones, in particular in areas on the periphery of the Mediterranean Sea, India, Australia, southern USA, and the African savannahs (Dan, 1985).

Also included are the *Grumosols* (brown and reddish-brown soils). The well-drained soils are defined as *Chromoxerpts* in the winter-rainfall areas, and *Chromousterts* in the summer-rainfall areas. The black or grey soils with poor drainage are *Peloxerpts* in winter-rainfall or *Pelousterts*, in summer-rainfall areas, respectively (Dan, 1985).

Inceptisols

Inceptisols are mineral soils, found in semi-arid, subhumid and humid regions. They have slightly more developed profiles than the Entisols; the surface horizons are lightly coloured and the subsurface horizons are less developed. They are generally found in recently formed areas, such as floodplains and steep mountainsides. A cambic (from L. *cambiare*, to change) horizon is an indication of at least some development that is characteristic of the soils of this order.

Ochrepts are well-drained soils, found in all climatic zones excepting the tropics. They have an ochric A horizon, and a brown, reddish-brown or red cambic B horizon. When further developed the Ochrepts become Alfisols. In the middle-latitudes are found various brown soils – Calcixerollic Xerochrepts and similar soils; these are usually medium, or medium–fine textured (Dan, 1985). The A horizon (10–25 cm) has a distinct crumb structure, with a moderate content of organic matter. It grades into a brown to dark-brown, coarse subangular blocky (B) horizon.

Brown soils are generally calcareous throughout and frequently the (B) horizon overlies a zone of lime accumulation. The silicate clays are dominantly of the illite and montmorillonite groups. These soils, which vary in depth from 30 to 50 cm, occur in areas with cool to cold winters, and with rainfall during the warm season. The soils are dry for most of the year and are only occasionally moistened throughout (FAO, 1964).

A number of other subgroups are found in humid zones, and are therefore not relevant in this context.

Histosols

Histosols comprise soils consisting of organic material extending from the surface downwards, or beginning within 40 cm of the surface, and in which at least half the soil in the upper 80 cm consists of organic material (EUROCONSULT, 1989).

Peat and similar soils are included in the Histosols. These soils are mostly found in the humid areas, but do occur in swamps in drier regions. They were formerly classified as interzonal soils, together with hydromorphic soils (Dan, 1985).

Saline soils

Formation and characteristics

Saline soils contain soluble salts in concentrations that impair crop growth. In the current US Taxonomy, their classification is based on the presence of salts distributed throughout the profile (hali-group) (see sodic and salic horizons).

Saline soils form under the the following conditions (Fitter and Hay, 1987): (a) coastal soils that are tidally inundated by sea water; these are dominated by Na^+ and Cl^- ions, and are characteristically wet (salt marshes); (b) in very dry inland areas in which ET exceeds precipitation; the influx of water, even with low concentrations of dissolved salts, may, in the course of time, cause massive accumulations of salt in the upper soil layers from which leaching is minimal. These soils are dominated by Na^+ and SO_4^{2-} (salt deserts); and (c) more rarely, soils rich in Na_2CO_3 result from volcanic activity.

Most saline soils are characterized by a low humus content, no differentiation into horizons (unless there is a salic, calcic, or gypsic horizon) and very little structure. The micro-structure is however stable, because the clay colloids are kept flocculated by the high salt content of the soil water. Consequently, their hydraulic conductivity is not less than that of non-saline soils (cf. Ch. 13).

The soluble salts of saline soils consist mainly of chlorides and sulfates of sodium, calcium and magnesium as well as potassium salts and nitrates (EUROCONSULT, 1989).

Many arid soils have a high content of soluble salts, which may have been derived from a variety of sources:

- (a) they may have resulted from the weathering of the parent rock without having been removed by the scanty precipitation;
- (b) they may have been brought in by the wind, originating in sea spray or from dry efflorescences of salt on the surface of other saline soils;
- (c) they may have risen to the surface, by capillarity, from mineralized groundwaters (the higher the water table, the greater the concentration of salts), if the water table approaches to within 2 to 2.5 m of the surface, the situation begins to become critical (Aubert and Kovda, 1967);

- (d) they may have moved laterally into a poorly drained basin, during flooding of the area; or
- (e) as a result of irrigation, without adequate drainage (cf. Ch. 13).

Because in arid regions the rainfall is not sufficient to leach them away, these salts tend to accumulate in the soil, while the high evaporation rate concentrates them near the soil surface.

A high proportion of the saline soils of the world are alluvial in origin. As a rule, they are of high potential fertility, which can be realized if the excess salts are removed by appropriate procedures (Kelley, 1951). Without such reclamation, crop production is either impossible or at a very low level of productivity.

Standards of salinity

Formerly, the degree of salinity of a soil was based on the dry-weight percentage of soluble salts (PSS). This parameter has been replaced by the electrical conductivity (ECe), at 25°C, (in mmho/cm) of the solution extracted from a saturated soil paste. The ECe gives the best correlation with cropping potentials in relation to soil moisture characteristics (EUROCONSULT, 1989).

The moisture content of the saturated paste (expressed in percentage of the weight of oven-dry soil) is called saturation percentage (SP).

The electrical conductivity of a salt solution is proportional to the PSS and inversely proportional (roughly) to the SP of the soil (EUROCONSULT, 1989).

Another useful parameter of soil salinity is the osmotic pressure (OP) of the soil moisture (expressed in atmospheres); the OP is directly related to the rate of water uptake by roots in saline soils. The following relationship, for ECe values within the range that permits plant growth, exists between ECe and OP (US Soil Salinity Lab., 1954):

$$OP = 0.36 \times ECe.$$

Saline soil types

There are three types of soils with excessive concentration of salts: saline soils, with excessive concentrations of soluble salts; sodic soils, with an excess of exchangeable sodium; and saline-sodic soils, which have a high concentration both of soluble salts and exchangeable sodium.

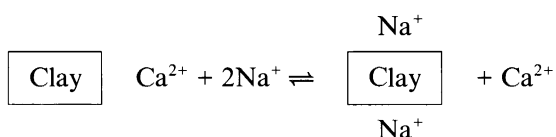
Saline soils (Solonchaks). These are soils in which the total concentration of salts has reached a level that interferes with the normal development of most crop plants. This usually occurs at levels exceeding 0.1% of soluble salts (Kearney and Schofield, 1936). A soil is considered to be saline if the electrical conductivity of the saturation extract is 4 mmho/cm or more, and the percentage of exchangeable sodium is less than 15 (Richards, 1954).

Sodium salts constitute only a relatively small proportion of the total salt content

of these soils, and sodium is consequently not adsorbed in significant quantities. The other salts that may be present in various proportions consist mainly of the cations calcium, magnesium, and potassium, and the anions chloride and sulphate – with, to a lesser degree, bicarbonate, carbonate, borate, and nitrate. The exchangeable ions are mainly Ca^{2+} and Mg^{2+} , the exchange complex being almost entirely saturated with these two ions.

In these soils, white salt-crusts appear on the surface and the pH is usually less than 8.5. Because of the large excess of soluble salts over exchangeable sodium, these soils are generally flocculated; soil structure is usually satisfactory and water-stable. The main cause of the negative effect on plant growth is the increased osmotic potential, with its concomitant reduction in availability of soil water.

Sodic (alkali) soils (Solonchaks). These are soils in which the total concentration of salts is not excessively high (less than 4 mmho/cm), but the proportion of exchangeable sodium is sufficiently high to affect plant growth adversely. When the ratio of soluble Na^+ to soluble $\text{Ca}^{2+} + \text{Mg}^{2+}$ exceeds 2, the sodium is capable of displacing calcium and magnesium in the exchange complex, and sodium is adsorbed on the surface of clay particles.



The degree of the saturation of the soil exchange complex with sodium is expressed as the *exchangeable sodium percentage* (ESP):

$$\text{ESP} = \frac{\text{exchangeable Na (meq/100 gr soil)} \times 100}{\text{cation exchange capacity (meq/100 gr soil)}}$$

The ESP is a good indicator of the structural stability of the soil and its physical response to the application of water. However, there is no sharp change in the properties of the soil as the ESP increases. In the past, the US Salinity Laboratory used an ESP of 15 as a boundary for sodic and non-sodic soils; more recently it has been recognized that it is necessary to relate the critical limit to the predominant clay type, because at a given level of ESP the physical properties of the soil are more adversely affected in soils with expanding 2:1 clay minerals than in those with non-swelling clay minerals. The accepted ESP boundaries are (EUROCONSULT, 1989):

montmorillonite	8,
illite-vermiculite	15,
kaolinite	22.

The equilibrium between cation concentrations in the soil moisture and cations adsorbed at the exchange complex is reflected by the relationship between the sodium adsorption ratio (SAR) of the saturation extract and the ESP.

The SAR is based on the exchange reaction between monovalent and divalent cations, and therefore gives a more accurate appreciation of sodium hazards because it relates more directly to the adsorption of sodium by the soil (Richards, 1954).

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{\frac{1}{2}(\text{Ca}^{2+} + \text{Mg}^{2+})}}.$$

The concentration of the ions is expressed in milli-equivalents per litre (meq/l).

An adjusted SAR (RNa) is replacing SAR in the literature; RNa takes into account changes in the concentration of calcium ions in the soil solution as a result of precipitation, or conversely, of dissolution of calcium compounds. RNa is an improvement over SAR because it provides better estimates of the ESP values of soils that are in equilibrium with the waters with which they are in contact. For most waters, the adjusted RNa values are not more than 10% higher than the corresponding SAR values.

The adsorbed sodium is not easily leached from the soil, unless it is in turn displaced from the exchange complex by sufficiently large additions of calcium to the soil.

When the clay calcium has been almost completely replaced by sodium, some of the excess sodium combines with soil CO_2 to form Na_2CO_3 . This increases soil pH, which may reach values of 8.5 to 10.0 (Richards, 1954). The sodium carbonate causes the dispersion of part of the soil organic matter, which becomes dissolved in the soil solution. The water rising by capillarity to the surface of such soils leaves behind a dark residue, called 'black alkali'.

As a result of the displacement of calcium and magnesium from the exchange complex, the clay particles also tend to become dispersed and soil structure deteriorates, with a resulting decrease in percolation rates. This is because the high Na^+ content causes deflocculation of the clay particles, the loss of air-filled pore space, and the soil becomes compact.

The dispersed clay particles tend to move downwards with rain or with the irrigation water; they are thus removed from the surface soil, which in due course may become coarse-textured. The eluviated clay accumulates at a lower depth, forming a dense, impermeable layer. As a result of alternate wetting and drying, typical morphological structures develop which have the form of columns, prisms, or blocks, when dry (Kelley, 1951).

Whilst the replacement of calcium by sodium in the exchange complex is a reversible process, the eluviation of the clay particles and the formation of zones of clay accumulation is irreversible – which may be the main obstacle to the reclamation of these soils.

When wet, alkali soils become plastic and sticky; after drying, hard clods are thrown up from them by tillage operations. Consequently it becomes very difficult to prepare a good seed bed, or to produce good tillage, where such soils are concerned. Moreover, plant growth suffers from inadequate aeration of the soil, low infiltration rates, and the formation of hard crusts on the soil surface after rains or irrigation.

Saline-sodic soils. Saline-sodic soils form as the result of combined processes of salinization and alkalization. They are soils in which a high content of total salts (greater than 4 mmho) is combined with a high proportion of exchangeable sodium (more than 15%); soil pH is usually less than 8.5. The high concentrations of soluble salts have a flocculating effect, which offsets the adverse tendency of adsorbed sodium to cause dispersion of the clay particles. Therefore, as long as the soil solution contains a high proportion of soluble salts, a more or less favourable soil structure can be maintained, and infiltration rates will remain relatively high.

However, when the soluble salts are leached out, in the absence of an abundance of calcium, the sodium clays become hydrolized, forming free sodium hydroxide. This deflocculates the clay particles, so that the saline-sodic soil is transformed into a sodic soil with its undesirable characteristics.

Dispersed soil conditions are usually evident at ESPs of 15 and above; however, a very strong soil structure, such as that of self-mulching vertisols (cf. p. 107) may counteract dispersion at ESPs well above 15. For example, good cotton yields may be obtained from Chromousterts with an ESP of 25 (EUROCONSULT, 1989).

If, however, sufficient gypsum is present in the soil, the leaching water dissolves the calcium, which replaces the exchangeable sodium concurrently with the leaching of the salts, effectively preventing the deterioration of the soil.

Table 3.3 provides a summary of saline and alkali conditions.

Factors influencing the formation of saline soils

Climate. Saline soils occur most frequently in regions of hot and dry climate. The aridity, high temperature, and high evaporation rates, are preconditions for a preponderance of evaporation over drainage, resulting in an adverse salt balance. Soil salinity may attain 75%, and the soils may be covered by a salt crust up to 50 cm thick in extremely arid deserts, such as those of Arabia and Chile (Kovda *et al.*, 1967).

TABLE 3.3

Major characteristics of saline soil types (EUROCONSULT, 1989)

Parameter	Saline	Sodic	Saline-sodic	Degraded sodic
ECe $\times 10^3$	> 4	< 4	> 4	< 4
ESP	< 15	at least 15	at least 15	varying
pH paste	< 8.5	8.5–10.0	usually < 8.5	< 8.5

Soils in deserts with a cold winter may also be highly saline. Here, the low solubility at low temperatures of certain salts is an important factor contributing to salinity.

Topography. A hot, dry climate is not sufficient in itself to cause the formation of saline soils. When the groundwater table is deep and evaporation from the soil is equal to precipitation, salts do not accumulate.

When an arid region lies in a deep depression, surrounded by mountain-chains, underground water flow carries dissolved salts into the dry area. As these waters are under considerable pressure, an 'artesian' rise of salts results in salt accumulation at or near the surface. These accumulations usually occur in secondary depressions, and give rise to *soluble salt pans* – the so-called 'sabhas' or 'shotts'.

Irrigation and drainage. Irrigation waters always contain salts, albeit of different kinds and in different concentrations. Water losses by evapotranspiration inevitably cause an increase in concentration of the salts in the root zone. The crop itself removes only infinitesimal amounts of salt: a cotton crop producing 4 tonnes of cotton-seed per hectare, removes barely 10 kg of sodium.

The rapidity with which salts accumulate in the root zone depends on a number of factors; these include the quality and quantity of irrigation water applied, the method of irrigation, and the adequacy of drainage.

Agricultural use of major soil types

Soils formed under extremely arid conditions

In areas with less than 50–80 mm of rainfall annually, are found typical desert soils. Vegetation is very sparse and is mainly restricted to dry riverbeds and occasional depressions. These areas include the Sahara, the Arabian Desert, the Atacama Desert, the Sonora Desert, Namibia, and parts of the Sind and Australian Deserts.

Desert soils are so little weathered that many soil scientists consider them to be still rock, and not soil at all. The physical condition of these media is usually favourable for plant growth.

Sand dunes are frequently encountered, the soils of which are Torripsamments. Because of the easy infiltration of rainwater and the easy availability of the water, these sandy areas have relatively favourable ecological conditions for plant growth.

In depressions with a relatively high water table, the so-called 'sabhas', the deposited soil is usually silty or sandy; the desert aquifers are always more or less saline as a result of the high evaporation rates and salinity increases as one moves from the periphery to the centre of the depression. The soils in the sabhas are Salorthids (Fig. 3.6) (formerly Solonchaks) (Dan, 1985).

Many of the desert areas are mountainous, with steep, bare, rocky slopes. The eroded coarse, gravelly soil from the mountainsides is deposited in the valleys.

The agricultural potential of the soils developed under extremely arid conditions depends to a large extent on their texture. The vast areas with a very coarse texture, such as stony desert Alluvium and shallow Regs are not suitable for agricultural production. By contrast, wide expanses of sandy soils, though deficient in plant nutrients, can be used with irrigation, even with relatively saline water, provided appropriate irrigation and fertilization methods are adopted.

Medium textured soils can be made productive, if no hardpan is present, after reducing salinity by leaching. Included in this category are the relatively fine-textured desert Alluvium soils. Even Salorthids (Takyric Solonchaks) can be reclaimed by appropriate methods (cf. Ch. 13).

Reg soils derived from relatively fine textured materials, in areas which were humid in a previous geologic period, can be made productive after leaching excess salts and drainage.

Soils formed under arid conditions

Areas with an average rainfall of about 80–220 mm in winter-rainfall areas, and up to double the latter figure, when most of the rainfall is in summer, are found on the margins of the Sahara, the Syrian Desert, large expanses in Central Asia, Iran, the Kahalari Desert, Central Australia, Western United States, and elsewhere.

The soil landscapes are similar to those of the typical deserts, but the soils are somewhat more developed. Their development is confined to very short periods every year, and is therefore extremely slow. Such soils have been subjected to very little leaching and, because of the sparse vegetation, are low in organic matter.

About half the total area of these soils is virtually devoid of vegetation, but much of the rest provides some browse.

Most soils of the arid areas, as a result of limited leaching by rainfall, are usually fairly well supplied with mineral nutrients, though these may be in poor balance with one another. Potassium is usually abundant, the content of phosphorus is relatively low, and deficiencies of micronutrients are quite common. Because of the sparse vegetation, these soils are low in organic matter and nitrogen.

Without irrigation, the Serozems are used mainly for rangeland for sheep. However, these soils have good physical characteristics and can be productive under irrigation. Soils with caliche crusts at or near the surface have little agricultural value (Dudal, 1980).

The least arid of these soil groups – the Brown Soils – are frequently used for dry-farming; yields on them tend to be low and erratic, and the risks of failure are high. A common characteristic of the arid soils is their lack of stability, and man's intervention usually results in erosion. When irrigated, they are easily leached if the drainage is good; but if drainage is poor, they are easily salinized.

Soils formed in semi-arid to subhumid areas

These areas are generally characterized by alternating dry and wet seasons. Vegetation and soil development are considerably influenced by the season in which precipitation occurs. In the winter-rainfall areas, the vegetation consists mainly of xerophytic scrub or forest; in the tropical summer-rainfall area, high savannah predominates, and in the middle-latitude temperate regions, high-grass prairies are the dominant natural vegetation.

A wide variety of soils is found in these areas for the following reasons: (a) a fairly wide spectrum of climatic conditions ranging from semi-arid to subhumid; (b) large areas were submitted to a different climatic regime in the geologic past; and (c) origin from widely different parent rocks (Dan, 1985).

Most of the soils of the semi-arid to subhumid areas are suitable for the production of a wide diversity of crops, both rain-fed and irrigated. Their productivity depends on their depth, but they are easily eroded. These soils are generally poor in phosphate, and respond well to fertilization – especially under irrigation (D’Hoore, 1964).

The *Vertisols* are an agriculturally very important order. The soil is very hard when dry, and very plastic and sticky when wet, so that their optimum moisture range for tillage is very narrow. During the dry season, draft power required for tillage is very high. During the rainy season, water may pond and the crops suffer from waterlogging. Primary tillage generally produces large, hard clods, which require much weathering, or many subsequent tillage operations, to enable an adequate seedbed to be established.

A large proportion of the deep *Vertisols* in India and in Africa are fallowed during the rainy season, because of the difficulties mentioned above, which prevent land preparation once the rains start, and adequate weed control thereafter. The exposure of uncropped soils to intense rains results in run-off and erosion, even in the presence of conservation structures such as contour bunds. Consequently, post-rainy-season crops grown on soil-stored moisture, such as sorghum, chickpeas, pigeonpeas and safflower are generally low-yielding. However, if a crop can be established during the early rains, erosion is reduced, and water is more efficiently used. A possibility is also created for double cropping, by means of intercropping or sequential cropping (Krantz, 1981) (cf. Ch. 16).

Under rain-fed conditions, the crops grown include pastures, wheat, maize, sorghum, soybeans, cassava, groundnuts, and pigeonpeas. Under irrigation the major crops are rice, sugar cane, and cotton. Large areas of the world’s *Vertisols* are still unused and constitute a reserve for future development (Dudal, 1989).

The *Alfisols* do not present the constraints related to acidity, calcium deficiency and aluminium toxicity that characterize many soils of the more humid tropics.

The *Alfisols* of the Indian subcontinent have a high potential for crop production under irrigation. Even with partial irrigation, grain yields of 5 ton/ha and more have been consistently reported for maize and sorghum. By contrast, yields of common

dryland cropping systems averaged about 0.35 ton/ha and rarely more than 1 ton/ha (El-Swaify et al., 1983).

The major constraints are: low water holding capacity, low aggregate stability, surface sealing by rains, heavy runoff and soil erosion. Subsurface layers of plinthite or hardpans are present over relatively large areas of the wooded savannahs. On these soils, erosion causes the surfacing of layers unfit for agricultural production (Dudal, 1980). Alfisols, because of their high infiltration rates, easily lose plant nutrients by leaching. They are also low in organic matter. Therefore N and P are the most limiting nutrients, and need to be supplied even in rain-fed cropping (El-Swaify et al., 1983).

Saline soils

The problems associated with the agricultural use of saline soils will be discussed in Ch. 13.

Formative elements of names used in the Soil Taxonomy (EUROCONSULT, 1989)

For the convenience of the reader, the formative elements of the names used in the Soil Taxonomy that appear in this chapter, are given below. For a comprehensive list, the reader is referred to EUROCONSULT (1989).

Formative element	Derivation	Connotation
Agr	L. ager, field	agric horizon
Alb	L. albus, white	albic horizon
Alf	from pedalfers (Al-Fe)	Alfisols
Anthropic	Gr. anthropos, man	anthropic epipedon
Aqu(ic)	L. aqua, water	aquic moisture regime
Arg	from argillic	argillic horizon
Ar	L. arare, to plough	mixed horizons
Arid	L. aridus, dry	
Bor	Gr. boreas, northern	cool
Cal	L. calcis, lime	calcic horizon
Camb	L. cambiare, to change	cambic horizon
Chrom	Gr. chroma, colour	high chroma
Dur	L. durus, hard	duripan
Ent	from recent	Entisols
Epipedon	Gr. epi, over and pedon, soil	surface horizon
Fluv	L. fluvus, river	flood plain
Frag	L. fragilis, brittle	fragipan
Glos	Gr. glossa, tongue	tongued horizon boundaries
Gyps	L. gypsum	gypsic horizon

Hapl	Gr. haplous, simple	minimum horizon
Histo	Gr. histos, tissue	soils rich in fresh or partly decomposed organic matter
Id	from arid, dry	Aridisols
Lithic	Gr. lithos, stone	presence of shallow lithic contact
Mollic	L. mollis, soft	good surface structure
Natr	natrium, sodium	natric horizon
Ochr	Gr. ochros, pale	ochric epipedon
Orth	Gr. orthos, true	the common ones
Ox	oxidation	oxic horizon
Pale	Gr. paleos, old	excessive development
Pell	Gr. pellos, dusky	low chroma
Petro	Gr. petra, rock	petrocalcic horizon
Plac	Gr. plax, flat stone	thin pan (placic horizon)
Plagg	Gr. plaggen, sod	plaggen epipedon
Psamm	Gr. psammos, sand	sand texture
Rhod	Gr. rhodon, rose	dark red colour
Sal	L. sal, salt	salic horizon
Sombr	F. sombre, dark	dark horizon
Spod	Gr. spodos, wood ash	spodic horizon
Sulf	L. sulphur	presence of sulfides
Torr	L. torridus, hot and dry	humid, warm
Ud	L. udus, humid	udic moisture regime
Umbra	L. umbra, shade	umbric epipedon
Ust	L. ustus, burnt	ustic moisture regime
Verm	L. vermes, worm	wormy, or mixed by animals
Verti	L. verto, turn	turn-over of surface soil
Xer	Gr. xeros, dry	xeric moisture regime

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CHAPTER 4

Water Resources; Conservation and Development

World water needs on the increase

The estimated increase in world population, at an average rate of about 2% per annum, signifies that the world water-demand will double henceforth about every 35 years (UN, 1964), at least for the time being. The increase in water requirements must be far more considerable in the dry regions than in the humid regions, for two main reasons: (1) that water is the limiting resource in the dry regions and therefore determines the extent to which other resources can be developed, and (2) that an increase in water requirements is concomitant with a rise in the standard of living. It is in the drier regions of the world that the standard of living tends to be the lowest, and therefore the rise should be the steepest.

Unfortunately, water resources are usually most abundant in regions in which they are least required, and scarce in those regions in which they form the key to agricultural development and, indirectly, to economic and industrial growth. Further, water supply is generally most abundant during the seasons of lowest requirement, and relatively scarce during seasons of peak requirements.

Population pressures and development needs have generally created a situation whereby the development of a new water resource is frequently possible only at the expense of previously available water supplies. Upstream removal of water reduces the amounts available downstream, and may even reduce the quality of the remaining water to unsafe levels; the development of new wells affects the output of older wells that depend on the same underground reservoir; conveying water from one region to another may limit future development of the donor region.

The existing shortage of water supply in the dry regions does not necessarily imply lack of water resources. In many of the dry regions there are potential water resources which, with the necessary know-how and funds, could be developed. Much additional water can also be made available by improving water conservation, by increasing the efficiency of use of existing water resources, and by a more rational allocation of water among competing demands.

Water conservation practices

Davenport and Hagan (1981), in assessing potentials for agricultural water conservation, distinguish between: (a) recoverable losses, such as those due to seepage, run-off, and deep percolation beyond the root zone; these are not true losses because they are recoverable for use on the farm or within the hydrological basin, where they increase groundwater supplies, (b) irrecoverable losses such as flows to oceans or highly saline sinks; or losses to the air, by evaporation from lakes, reservoirs, from the soil, etc.

Increasing water storage in the root zone

The solum as a moisture reservoir

The soil, to the bottom of the root zone, constitutes a moisture reservoir of vital importance to agriculture. Water that infiltrates into this reservoir can be stored with relatively little loss for fairly long periods – longer than is generally realized.

In humid climates, the amount of water that is stored in the soil depends on the water-holding capacity of the soil, and therefore heavy soils are more effective in this respect than sandy soils. In arid climates, it is the amount of precipitation that is the limiting factor; therefore, sandy soils are better water reservoirs for rainfall than are heavy soils: percolation in the latter is slower, the depth wetted is less, and thus the proportion of precipitation lost by run-off and evaporation is greater.

In the Mediterranean region, crops such as sorghum, melons and sesame, can be grown during the hot summer months, without receiving a drop of rainfall from sowing to harvest; they can produce high yields on the moisture stored in the soil during the winter months. In the Great Plains of North America, numerous investigations have proven that the amount of moisture stored in the soil, prior to the sowing of winter wheat, largely determines the yield level that can be expected (Pengra, 1952). In irrigation farming, it is good practice to wet the soil to the full depth of the root system before sowing the crop, thereby forming a reserve of water on which the plant can draw throughout its growing period.

The amount of precipitation taken in by the soil depends on run-off and infiltration. By reducing run-off and increasing infiltration, the amount of water stored in the soil can be increased – with beneficial effects on crop production, provided the total amounts of rainfall are sufficient.

Run-off control

It is somewhat paradoxical that the drier the climate is, the greater will be the havoc caused by rainfall. Precipitation in arid regions generally occurs as torrential rains, the sparse natural vegetation affords very little protection to the soil, and infiltration rates are rapidly reduced while run-off is increased. Most soil-conservation methods, such as strip cropping, contour ploughing, terracing, etc., aim at reducing run-off,



Fig. 4.1. Aerial view of run-off control in tributary valleys in the desert by the Nabateans. The flow of water was slowed down by a series of stone levees; gradually the areas between the levees became level as a result of the deposition of silt, so that terraces were created which were sown after the floods. The Bedouin cultivate these patches up to the present day, obtaining yields of barley even in dry years. Photo Soil Conservation Service, Israel.

and are therefore also effective in increasing the amount of water that is stored in the soil.

The protection provided by vegetation is usually a major factor in run-off control. Plants intercept part of the rainfall and reduce the velocity of raindrops; they also obstruct or slow down the movement of water on the soil surface (Fig. 4.1). The indiscriminate destruction of the plant cover in watersheds increases soil erosion and causes excessively rapid run-off that cannot be controlled.

Increasing infiltration

The maintenance of a high infiltration rate is an important objective of soil management; it reduces run-off and thereby increases the efficiency of rainfall and irrigation, at the same time minimizing soil losses by erosion.

The rate of infiltration of water into the soil depends on soil structure, soil cover, the degree of dryness of the soil, and the intensity and duration of the rainfall or irrigation. As rain falls on a bare soil, the surface aggregates are destroyed by the

impact of the drops of water and the pores of the soil surface become clogged with fine particles; this rapidly reduces the rate of infiltration of the water.

The surface of many clay soils can be easily sealed, and infiltration capacity reduced drastically, by a few minutes of heavy rainfall (Jacks et al., 1955). Mulches of straw or crop residues, by breaking the impact of the raindrops, markedly improve infiltration (Fig. 4.9). Mulching was also found to reduce run-off by about half the amount that occurred without mulching (Zingg and Whitfield, 1957).

Cultivated row-crops, such as cotton, maize, and peanuts (groundnuts), usually afford less protection against the effects of rainfall on the soil than do densely growing crops such as herbage and small grains, and therefore their soils tend to have a lower infiltration rate. The frequent cultivations which they require also reduce soil aggregation. The same is true for soils with a high stability of soil structure, such as results from a high organic-matter content. Hence, all factors that improve and maintain soil structure, also improve infiltration, and vice versa. However, if the subsoil is impervious, run-off will eventually occur even with a very permeable topsoil.

Whenever the rate of water supply is in excess of the rate of infiltration, ponding or run-off will occur.

Conserving snowfall

In the middle-latitude semi-arid areas, a considerable proportion of the precipitation is in the form of snow (cf. p. 50). In the Central Great Plains of the USA, e.g. snowfall north of latitude 39° exceeds 600 mm, with an average water content of 72 mm per season and provides 30–55% of the soil water recharge during fallow (Greb, 1983). De Jongh and Steppuhn (1983) write that the manipulation of the snow cover offers the greatest potential for increasing available water for dryland crops on the Canadian Prairies, where about one third of the precipitation falls as snow.

The snow removed by wind from the cultivated fields is generally deposited in ditches, fence rows, or other barriers. Management of the snow cover has two objectives: (a) to trap and hold the snow where it is wanted; and (b) to hold the snowmelt in place until the soil thaws enough to allow infiltration. The major strategy is to reduce wind velocity, mainly by leaving upright stubble or field shelterbelts (Willis, 1978).

Standing stubble of small grain crops is very effective in trapping snow, and cutting swaths at alternate heights is still more effective (Nicholaichuk, 1980). Fall tillage operations should leave the stubble as undisturbed as possible (De Jongh and Steppuhn, 1983). Snowmelt storage efficiency in undisturbed stubble averaged 53%, over a 16-year period (Greb, 1983).

The water table as a source of moisture supply

The presence of a high water table is of importance in determining the amount of water available to the crop. If the water table is near to the soil surface, the root zone

of the crop will be confined to a shallow soil layer, with adverse effects on crop production, as groundwater rises to the soil surface by capillary flow, and may cause a dangerous accumulation of salts in the root zone. If the water table is sufficiently low not to interfere with normal development of the crop, a deep-rooted crop may obtain part of its water requirements from the capillary fringe of the water table.

A fluctuating water table is most dangerous, making it impossible for plants to adjust their rooting systems in the manner which they are able to do with a constantly shallow or a relatively deep water table. When the water table rises, roots are killed; when it recedes, the shallow soil layer rapidly dries out and there are no roots to supply moisture from the lower depths. Lucerne, e.g., which is normally deep rooted, will make good growth on soils with a relatively high water table, provided it is stable; if it fluctuates, the lucerne will be rapidly killed.

Appreciable quantities of water can move upwards, sufficiently to be used by plants, from depths of as much as 180 cm below the root zone (Gardner, 1964). Upward movement from a not-too-shallow water table can, therefore, under certain circumstances, make an important contribution to the water economy of plants.

Water harvesting

Run-off conditions in arid zones

In humid climates, run-off usually occurs when rain falls on a saturated soil. The more arid the region, the rarer are situations in which the soil is saturated by rainfall, and the more frequent is the occurrence of run-off from soil that is not saturated, following rains that exceed a certain intensity. It has been estimated that, in the central Sahara, a flood will occur when rainfall exceeds 5 mm with an intensity greater than 0.5 mm per minute (Dubief, 1953). Many soils of arid regions have a very low absorption capacity for rainfall. The sparse vegetation, the large proportion of bare rock, the low organic-matter content, and the hard impermeable crusts that form after the first minutes of rainfall, are all contributory factors.

Under very arid conditions, reducing run-off and increasing infiltration rates are ineffective, as the amounts of moisture that can be stored in the soil do not, in any case, suffice for crop production. Rather should efforts be made in the opposite direction: to increase run-off and reduce infiltration in certain areas which then serve as a source of water supply for other areas.

Water harvesting has been defined as a technology "which uses collected run-off water for storage in soils, behind dams, or in gullies; for artificial recharge to aquifers; or captured in-place on contour ridges, terraces or tied-ridged agricultural fields" (Perrier, 1988).

Water harvesting is a centuries-old practice (cf. p. 127), but has been abandoned and largely forgotten. High pumping costs, depleted aquifers and the need to make crop production possible in areas with insufficient precipitation and no available water resources has rekindled interest in water harvesting technology. It is also being



Fig. 4.2. Reconstructed Nabatean farmstead, using modern agricultural production technology. The water donor area and the farmstead itself remained in their original condition, with minor repairs to the conduits to, and the levees within the agricultural area. Photo Soil Conservation Service, Israel.

used in some semi-arid areas where rainfall is normally sufficient for crop production, to reduce risks of crop failure in years of drought (Papendick and Campbell, 1988). It is currently practised, in one form or another, in dry areas in Australia, the USA, the Middle East, and the Indian subcontinent (Pandey, 1991).

In many dry regions, in which contemporary precipitation alone is not sufficient to ensure a crop, harvested water, plus that accumulated in the soil, will suffice if a proper ratio between donor area and recipient area is established. In research carried out on a reconstructed Nabatean farm in the Negev Desert (Fig. 4.2), it was found that total annual run-off was 15–20% of total annual rainfall (Evenari et al., 1971). Therefore, with an average rainfall of only 100 mm, run-off from a catchment area 20 times as large as the recipient area, can contribute 300–400 mm in addition to the 100 mm; the equivalent of about 400 mm, if we assume an efficiency in run-off collection of 80%.

Overall, rainwater harvesting is a feasible proposition for areas with as little as 50–80 mm average annual rainfall (NAS, 1974). Two factors are important for successful production: the frequency and amount of rainfall and the run-off characteristics of the donor area (Kamra et al., 1986).

More recently, the possibility of using water harvesting in areas of the semi-arid tropics with sufficient rainfall for crop production (average annual rainfall higher than 750 mm) is being investigated.

When a rainy season crop is grown in these regions on deep Vertisols, the following dry season crop often cannot be established because the upper soil layers become too dry at the sowing time of the next crop.

Water harvesting would, in this case, enable the production of a second crop, and eventually to provide supplementary irrigation to this crop later in the season. An important complementary component of this approach is to provide storage of any excess water in the watershed for subsequent use for supplementary irrigation (Pandey, 1991).

Rees et al. (1991) point out that without a storage device, the crop can be damaged by waterlogging caused by too great a concentration of water on soils with low permeability, if the water is applied directly to the cropped area.

A novel initiative, is the use of water harvesting for the reclamation of alkali soils on the Indo-Gangetic plains (cf. Ch. 13) (Kamra et al., 1986).

Nabatean water harvesting

Rainfall water harvesting was developed to a fine art by the Nabateans.

The Nabatean Kingdom flourished from the 2nd century B.C. to the 7th century A.D. It was essentially a desert kingdom, extending from Damascus to what is now Saudi Arabia (Evenari and Koller, 1956). The Nabatean economy was based mainly on the commerce between the Near and the Far East. Petra, its capital in the middle of the desert, was at the crossroads of the caravan routes. A number of important towns, also in the desert, were set up to protect these routes. By developing an elaborate system of rain catchment, including dams, spillways, and terraces, the Nabateans were able to produce in the desert itself, with an annual rainfall of less than 100 mm, the food required for their towns and for the caravans travelling through their territories (Fig. 4.3).

Many thousands of farmsteads were established in small tributary wadis, surrounded by barren hillsides. All these farmsteads had two basic features: (a) a water catchment area, divided into subcatchments by water conduits which collect run-off from the hillsides and lead it to (b) a cultivated terraced area in the wadi bottom. A rainfall of 50–100 millimeters in the catchment area permitted the storage, in the field area, of the equivalent of several hundred millimeters of rainfall (Figs. 4.4 and 4.5).

Modern technology is attempting to develop more effective methods, aimed at reducing the ratio between donor and recipient areas.

Microwatersheds

For borderline rainfall situations, effective methods have been developed whereby run-off from parts of a field serves for direct use or storage on another part. The



Fig. 4.3. Aerial view of the ruins of the Nabatean desert town Ovdad, surrounded by farmsteads based on water harvesting. Average annual rainfall: less than 100 mm. Photo Soil Conservation Service, Israel.

donor area may be small: one or two ridges or tilted beds, and the receiver area may be the furrow in which the crop is planted.

A usual approach is to sow the crop in narrow strips between wide intervals that are ridged as artificial miniature watersheds. These latter are compacted to increase run-off of water to the crop rows. The relative widths of the water-shedding strips and of the crop-producing strips depend on the amount of annual precipitation that can be expected. The usual ratios are from 2:1 up to 4:1 (Fig. 4.6). This system is considered to be more efficient than fallowing, in which water is conserved from one season to the other and the entire area is cropped in one year out of two (see Ch. 16) (Kemper, 1964).

Various methods for increasing the run-off from the water-supplying strips are being investigated in the arid west of the United States, in Israel, and elsewhere. The two main approaches used are (1) ground covers of plastic films, rubber, or metal sheeting materials, and (2) waterproofing and stabilizing soil surfaces by spraying with low-cost materials (Myers, 1967).

Thin plastic, rubber, and metal films have been used for building precipitation catchments. In one case, minor surface ridges were formed which were almost completely covered (as to 90%) with a plastic film, in order to concentrate rainfall pene-



Fig. 4.4. Nabatean water harvesting (Third Century). The water donor area has been cleared of stones, to increase run-off. Photo Soil Conservation Service, Israel.

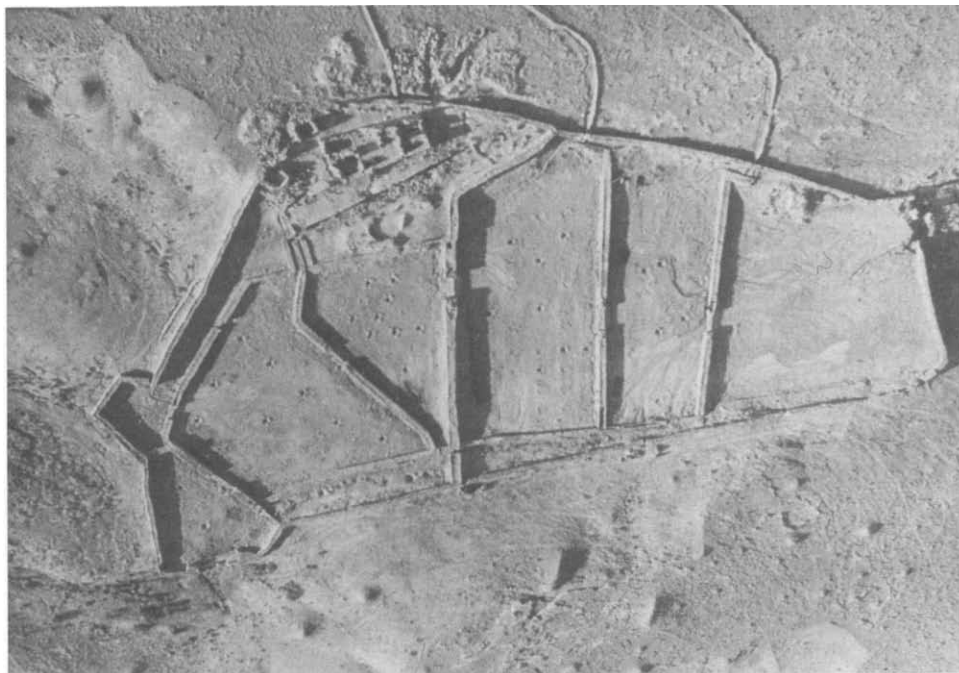


Fig. 4.5. Nabatean water harvesting (Third Century). Aerial view of a farmstead based on water harvesting. Note the water conduits, which are still functional, leading from the donor area to individual fields. Photo Soil Conservation Service, Israel.

tration into the uncovered part. Results showed that the covering was effective in increasing the soil moisture content, as well as the yields and water-use efficiency of maize, which served as an indicator plant (Willis et al., 1963).

The main disadvantages of the various films are the high cost and susceptibility to damage by winds. Research is continuing on developing new, less expensive and more durable materials, as well as methods of reducing damage – such as bonding the films to special asphalt pavements (Myers, 1967). The most immediately promising approaches, however, appear to be the waterproofing and stabilizing of the soil surfaces.

The simplest of these methods consists of creating a cleared smooth surface. On a well-structured clay-loam soil, with a 4% slope, this method produced 21% run-off of a 195 mm rainfall (Hillel et al., 1967). However, this method is applicable only when erosion hazards are minimal. Sodium salt can be used to reduce infiltration, by dispersing the soil colloids and sealing soil pores. Using sodium carbonate at the rate of 45 kg/ha, 70% run-off was obtained from a cleared and smooth clay-loam soil (ibid.). This method, too, is dependent on effective erosion control, in the absence of which the treated soil may be removed within one season.

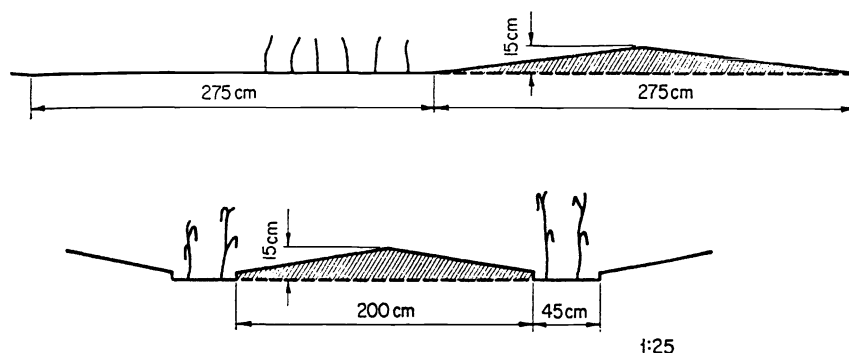


Fig. 4.6. Microwatersheds. Above: microwatersheds for small grains. Below: microwatersheds for row crops. From Kemper (1964). By courtesy of the US Department of Agriculture.

Another method, called 'catchment basins', has been developed for use on relatively even sloping plains (with slopes up to 5%). The area is divided by small earthen strips into gently sloping rectangular plots. The entire run-off collects at the lower-most corner of each plot, in a planting basin. The method is most suitable for planting orchard trees (Shanan and Tadmor, 1976) (Fig. 4.7).

In Balochistan (Pakistan), small catchment basins were prepared on valley-bottom soils by simple ploughing and physical desintegration of soil aggregates, leading to crust formation following the impact of the rain on the soil surface. Results in the second year were better than in the first year, because crust formation had improved (Rees et al., 1991).

A number of water-repellent treatments with materials such as silicone, to make the soil hydrophobic, have given encouraging results. Finally, sprayed asphalt appears to offer promise of providing a relatively low-cost and enduring sealing and binding coating (Myers, 1967).

Conservation bench terraces

A new terrace system for semi-arid regions has been designed by Zingg and Hauser (1959) that not only reduces water erosion, but also spreads run-off water over a levelled bench, where it is stored in the soil for use by the crop (see Fig. 4.8).

Early experience in the field with these terraces showed that good results can be achieved with this method, provided that (1) precision levelling is carried out, (2) there are adequate terrace outlets to handle excess water, and (3) fertilizers are applied so that the stored water is used efficiently. In a region with an average rainfall of 470 mm (mainly summer rainfall in the south-western Great Plains), it is recommended to use one-third of the field area for establishing the terraces, and the remaining two-thirds for watershed areas (Hauser and Cox, 1962).

The system was tested at several sites in the US Great Plains and in India. Hauser

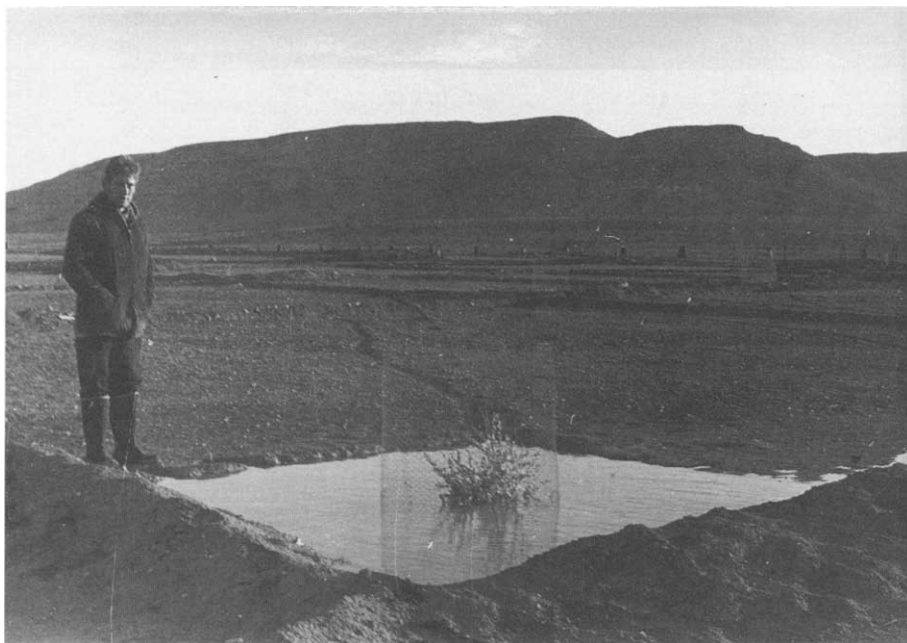


Fig. 4.7. Fruit tree planted in micro-catchment basin, in an area with 100 mm rainfall. Photo Soil Conservation Service, Israel.

and Jones (1988) report that it increased water-use efficiency and whole farm production when built on deep fertile soils with fine texture and moderate to slow infiltration rate, and that the system was profitable under a wide variety of conditions. In this plan, relatively drought resistant crops are sown on the upper, water donor areas, and those more demanding in their water requirements are sown on the lower areas.

Whilst the conservation bench terraces system has great merits, a number of disadvantages have limited its acceptance (Johnson et al., 1983):

- construction costs are high;
- the severe land scraping involved in shaping the terraces reduces soil productivity (cf. Ch. 14);
- yields on the water-receptient areas are increased only in years with substantial run-off.

Reducing evaporation losses from the soil

Soil mulches

At the beginning of the century, King (1914) carried out his 'classical' experiment from which he claimed that a surface mulch of dry soil 5–8 cm deep, by obstructing

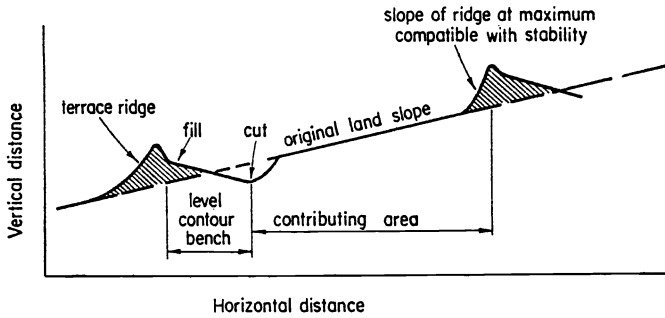


Fig. 4.8. Cross section of the slope-control practice of conservation benching. From Zingg and Hauser (1959). By permission of the American Society of Agronomy, Inc.

the rise of water to the surface through capillary action, effectively reduced loss of water as compared with a soil having an undisturbed surface. Rarely has a mistaken conclusion drawn from an otherwise impeccable experiment given rise to such a wasteful practice as the frequent cultivations for moisture conservation adopted subsequently for many years in most dry regions.

In King's experiment, glass cylinders that were open at both ends, and each containing a column of soil, were placed with one end resting in a shallow water container. A comparison was made between cylinders with an undisturbed soil surface and those with a dry surface mulch resulting from frequent stirring of the topsoil.

It was found after 100 days, that the surface mulch had reduced evaporation losses by 50%. The only flaw in the conclusions and subsequent application of these results was that capillary rise of water to the soil surface is effective only when the water table is sufficiently near to the surface; under these conditions, increased loss of water from the soil is probably more beneficial than detrimental!

Following on King's experiment and conclusions, a soil mulch for moisture conservation became standard procedure in dry regions, and dicta such as: 'two cultivations can replace one irrigation' became very popular. The too-frequent cultivations impaired soil structure, however, and increased soil losses by erosion. These effects were most pronounced on the row-crops, such as cotton, maize, and soybeans, which, for this reason, gained the reputation of being soil-destroying crops.

It has since been shown that after a rainfall or an irrigation, the top 7–10 cm of the soil dry out rapidly; in any case it would be impossible to prevent this loss by cultivation, because the drying out had already taken place by the time the soil surface was sufficiently dry for cultivation to be possible. Below the dry layer, moisture loss by evaporation from the soil becomes minimal, and further water losses are mainly due to plant transpiration – hence the favourable effect of weed control on water losses which are thereby reduced.

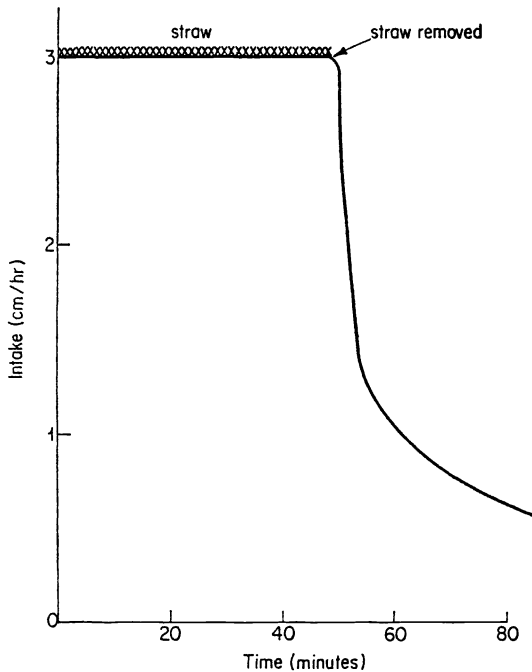


Fig. 4.9. Effect of straw mulch on water infiltration. From Duley (1939). By permission of the Soil Science Society of America, Inc.

Straw mulches

As opposed to the ineffectiveness of a 'dust mulch' to reduce evaporation, straw and the other crop residues left on the soil surface have proved to be very effective (Fig. 4.9). It has been estimated that a straw mulch saved the equivalent of 50 to 75 mm of rainfall in dry weather (Stephenson and Schuster, 1946). The use and importance of stubble mulches will be discussed in detail in Ch. 14.

Chemical treatments

Experiments have been carried out with the object of reducing evaporation from the soil by using suitable chemicals. It has been found that hexadecanol mixed with the surface $\frac{1}{4}$ in of the soil, reduced evaporation by 43% (Olson et al., 1964). This material, which is resistant to microbial activity, remained effective for more than a year. The surface layer of treated soil dried out more rapidly than that of untreated soil, creating a diffusional barrier to evaporation. Fewer cracks developed in the treated than in untreated soil, and the hexadecanol also increased aggregate stability.

It has been shown that chemical weed control resulted in moisture storage that was equal to that achieved under stubble mulch and subsequent tillage, when the initial moisture conditions were equal (Wiese and Army, 1960).

Weeds are one of the major maintenance problems on canal banks and irrigation channels. They reduce the carrying capacity and decrease the velocity of flow, thereby increasing sedimentation. By raising the water level in the canals, they increase seepage losses – with a resulting rise in the water table of the adjoining land, and increased salinity problems.

Principal water resources

Irrigation water may be drawn from the natural flow of streams and rivers, from reservoirs that make it possible to regulate the flow of streams, from underground sources by means of wells, and increasingly from unconventional sources such as the use of effluents and, in prospect, water desalination.

Surface waters

Streams and rivers

The streams and rivers in arid regions are of three types:

- (a) ephemeral streams that originate within the region;
- (b) streams that originate in a humid watershed, in close proximity to the arid lands, and usually from higher altitudes within the region; and
- (c) perennial rivers that originate in distant humid climates and flow through the arid region.

Ephemeral streams

In arid areas approximately 5% of the storms cause over 50% of the stream flow, and approximately 15% of the floods produce nearly 90% of the stream flow (Burgy et al., 1967). Small rains, and even large rains of low intensity, do not generally yield any water for stream flow. Floods in arid regions, when they do occur, are usually destructive. The barren, and frequently steep, land surfaces cause rapid run-off, and the water soon flows with torrential speed along the previously dry beds of the numerous channels. Even a rainfall of 10 mm on a watershed of 50 km² may cause a flash flood.

In arid regions, springs with a copious and continuous flow of water are relatively rare. Stream flows that originate within the region are usually intermittent in nature: torrential flows may occur for a few days or even hours at a time, to be followed by long periods during which the stream bed is completely dry. Certain streams flow fairly continuously for a few months during the rainy season, and then dry up progressively.

Floodwater spreading

In most desert and semi-desert regions, flash floods occur during which enormous amounts of water sometimes stream through the previously dry channels for short periods of time, varying from a few hours to a few days. These waters can be diverted, partially or entirely – depending on their volume and velocity – to inundate fields especially prepared for this purpose.

Essentially, techniques for such floodwater spreading have not changed markedly in comparison with those used by primitive people, as described in Ch. 12.

A diversion dam is erected at a suitable location in the stream channel, to direct the water into a ditch – the dimensions of which are calculated in accordance with the velocity and size of the stream to be diverted. The slope of the ditch has to be so adjusted as to ensure that the velocity of the stream is reduced to manageable proportions, or else the ditch will be rapidly destroyed. The velocity must be sufficient to reduce sedimentation to a minimum, as otherwise it would soon put the ditch out of service.

The dams themselves can be relatively simple earthen structures on small waterways; on larger stream channels, however, more elaborate structures are required which may make the whole method uneconomical (Fig. 4.10).

Sedimentation may, in the course of time, raise the soil level of the watered fields to such a degree that water spreading is no longer possible, unless the dam is relocated. In order to avoid this contingency, the water may first be released into sedimentation basins. These have the additional function of enabling some degree of regulation of the flow of water to the fields to be irrigated, as they can accumulate a larger quantity of water in a short time than could be effectively spread in the field. The field itself should be prepared as for ordinary irrigation. Basin irrigation is the most suitable method for water spreading. The ditches will usually be much larger than conventional irrigation ditches, in order to handle relatively large streams of water. The main difference of water spreading from conventional irrigation is that, in the former, water is not applied in accordance with crop requirements but whenever it suddenly becomes available.

The water can be applied before sowing in order to wet the root zone to an appropriate depth. It can also be applied to a growing crop. The most suitable crop for this purpose is a perennial grass or a legume such as lucerne, that is capable of withstanding long periods of drought, but reacts quickly to favourable soil moisture conditions.

In view of the unreliable supply of water it is doubtful whether stable crop production, providing an acceptable standard of living to modern farmers, can be based exclusively on water spreading methods. These may, however, play a useful role in producing forage reserves for supplementing range grazing, as an adjunct to irrigation farming, or as a supplemental moisture supply in semi-arid regions where rain-fed crops are a possibility.



Fig. 4.10. Low Nabatean diversion dam, constructed across a stream channel, for floodwater farming. Photo Soil Conservation Service, Israel.

Lasting rivers and streams

Many rivers originate in relatively close proximity to arid land – usually at higher altitudes, where they are fed by melting snows and the water serves to irrigate the adjacent arid plains. Examples are the Syr Daria and Amu Daria of Soviet Asia, the Tigris and Euphrates of Iraq, the Sacramento and San Joaquin of California, and the Murray of Australia.

Others rivers and streams originate in humid climates that are very distant from arid regions. If, like the Congo River, they flow at constant tropical latitudes, they remain within the humid region, and the enormous amounts of water which they collect are discharged into the ocean. If, however, they flow meridionally like the Nile, their waters eventually reach an arid region and can serve for irrigation.

Interregional transfer of waters

The development of many arid and semi-arid regions is apt to be dependent on the transfer, by canals or other means, of waters from streams flowing in more or less distant humid regions. A few examples are: the transfer of the waters of the Indus and its tributaries by canal to the arid Sind and the semi-arid Punjab; the waters of the Colorado River also transferred by canal, to the Imperial Valley in California; and

transporting the water from the sources of the Jordan in Upper Galilee in a system of open channels and closed large-diameter pipes to the Negev Desert in southern Israel.

In many cases, waters of one river system are transferred through canals and tunnels to a different river basin, to supplement the water supply of the latter.

A recent plan for the Sudan involves the cutting of the World's longest canal (280 km – the Jonglei – through an elbow of the Upper Nile. The objective is to drain the Sudd swamp, and to irrigate millions of hectares in Sudan and Egypt (Tinker, 1978).

Watersheds

“A watershed is an area of land and water bounded by a drainage divide within which the surface run-off collects and flows out of the watershed through a single outlet into a larger river, lake, or other body of water” (Brown, 1960).

Small watersheds

Drainage areas of up to a few tens of thousands of hectares are considered as small watersheds.

Research on soil and water conservation and management on a small watershed basis in semi-arid tropics has been conducted by ICRISAT since the early 70's. Of the several methods tested (Fig. 4.11) systems of graded terraces and furrows, draining into graded terraces and waterways, appear to have the greatest potential for manipulating run-off, conserving water and preventing erosion. Instead of run-off being concentrated in large streams, excess water is partly stored in tanks, and the remainder is conveyed off the land in a number of small streams. On light soils, the ridges can be tied (cf. Ch. 14) (Kampen and Krishna, 1975).

A more detailed description of the system is presented in Ch. 8.

Large watersheds

Larger drainage areas are usually called river basins. In general the tendency in dry regions is for closed drainage basins to occur, in which sediments accumulate. Saline lakes are also of frequent occurrence (Dixey, 1966).

An ideal watershed management project would integrate plans for soil conservation, soil improvement, irrigation, drainage, flood prevention, and development of water supplies for all purposes. It requires community cooperation, organized administration, taxation, and political action (Brown, 1960).

The relative proportion of local precipitation that remains as surface run-off or that sinks into the ground to join the underground aquifers, depends largely on the types of rock and overlying soil. Fine-textured clays and shales are relatively impermeable and, especially when torrential rains occur, a large proportion of the precipitation contributes to run-off. By contrast, limestone rock and its derived overlying

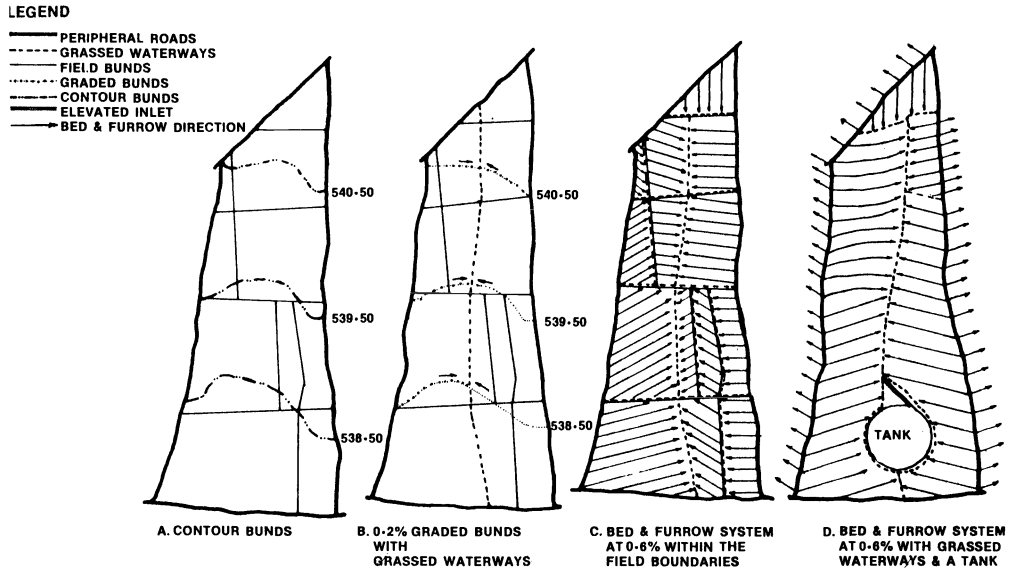


Fig. 4.11. Four possible soil and water conservation and management practices illustrated for a small Vertisol watershed. Systems A and B are difficult to use because farmers do not want their fields bisected, in practice, the bunds are placed on field boundaries and cause water stagnation and bund breaching. The bed-and-furrow system (C) at 0.6% slope was established five years previously and proved satisfactory. System D is the one that has given the best results. From Krantz et al. (1978). By permission of the American Society of Agronomy, Inc., and the Soil Science Society of America, Inc.

soil readily absorb rainfall; most of the precipitation falling on it that is not used for evapotranspiration, eventually joins the underground water reservoir (Dixey, 1966).

The kind of vegetation that is established on the watersheds will determine to a large extent the amount of water that percolates deeply and replenishes the water table and consequently the water yield from springs and streams. In California, the control of large areas of brush and its replacement by a cover of grasses increased the amounts of water available to the underground water reserves (Biswell and Schultz, 1957). Water yields from forest land can also be increased by altering the type of vegetation. In North Carolina, cutting the woody vegetation on an entire drainage area increased the water yield by 65% during the first year after cutting (Storey, 1960).

Strip-cutting of pine increased water yields by about 30% (Love, 1960). Trees and brush species usually have a dense canopy, causing a high ratio of interception to loss; they grow throughout the dry season and, having a deep root system, use all the water available to a considerable depth.

In the drier regions, grasses usually become dormant during the dry season. They intercept less of the precipitation, and use less of the available water in the soil, than

do most shrubs, so that with them more water becomes available for the recharge of aquifers.

In general, changing or removing the vegetation in order to increase deep percolation is effective only in regions with sufficient rainfall. Where precipitation is low, virtually all the moisture will either be lost from the soil by evaporation in the absence of a plant cover, or, if much vegetation is present, will be used for evapotranspiration. This is regardless of the *nature* of the plant cover: changes in vegetation are effective in increasing water supplies only where precipitation occurs as snow or is sufficient to saturate the soil frequently (Price, 1956).

Control of surface water

Disastrous floods are of regular occurrence in many arid regions, affecting small to large areas. Their occurrence and size depend on the rate, duration, and extent, of rainfall, and on the condition of the land on which it falls (Ford et al., 1955). When the resulting run-off exceeds the capacity of the stream channels, floods result. Contributing factors include permanent or accidental barriers in the stream, siltation, and the breakdown of dams or dykes. Crops and pasture are damaged, floodplains are eroded and gullied or covered with infertile sediments, water control systems are destroyed, etc.

Flood control includes the following measures (Ford et al., 1955):

- (a) *Land treatment*: reducing run-off and increasing infiltration on the lands of the watershed, by mechanical and vegetative methods, will lessen the amounts of water and sediment that reach the farm drainage ways and the small streams.
- (b) *Upstream waterflow retardation*: is based on appropriate measures in the small streams and tributaries of the watersheds, such as stream channel improvements to increase water-carrying capacity, gully stabilization works, floodwater retarding structures, sediment detention basins, etc.
- (c) *Downstream flood-control measures*: consist of large reservoirs and levees constructed on the major waterways to control the flow of floods in the major river valleys.

Reservoirs

The more arid the region, the greater the seasonal fluctuations in the flow of surface water. Reservoirs are meant to achieve a more regular water supply by correcting the great variation in stream flow; but the larger the reservoir, the greater the evaporation losses, so that complete stabilization of surface flow is not possible in an arid climate (Langbein, 1962). However, in the absence of a reservoir, it is the periods of minimum flow which usually coincide with periods of peak requirements that determine the quantities of water which can be relied on for agriculture.

Reservoirs are basically of two kinds (Riesbol et al., 1967):

Onstream: the reservoir is fed directly by the stream and therefore receives the entire sediment load. It must store the maximum floods, or pass off the excess water. The Aswan Dam is a typical example.

Offstream: the reservoir is fed by diversions from the stream; it receives only part of the sediment load and must store only part of the floods.

In many arid regions of the world, spectacular works are undertaken to store river water on a large scale. Enormous masonry dams are built, behind which artificial lakes are formed. Evidence is increasing that in many cases these projects are ill-conceived; they are also always expensive and moreover extremely wasteful of water. Evaporation is very high in the arid regions which they are to serve and in which they are located, amounting to as much as 125 cm annually (Stamp, 1961).

As much as three-quarters of the water stored may be lost by evaporation (Dixey, 1966), and the remaining water becomes increasingly saline. As a result of the extremely high rate of evaporation, the total yield of a watershed in an arid region is actually decreased when large reservoirs are built. There is even a point at which the building of additional reservoirs causes a net deficit in usable water – when aggregate evaporation losses exceed the amounts of usable water gained (Burgý et al., 1967).

“Reservoirs are also mortal”, according to Addison (1961). Experience in South Africa has shown that reservoirs have filled up with sediment within a dozen years. In the Levant and in Sinai, relatively small reservoirs have filled up in a still shorter period. It is true that certain reservoirs have a longer life-expectancy: in the USA, the great reservoirs are expected to remain effective for one or two centuries (ibid.). However, even in the USA there are examples of reservoirs that have silted up completely within a few years (Stamp, 1961).

Reduction of evaporation losses

Evaporation is usually the principal cause of water loss from reservoirs and may assume considerable proportions.

In constructing reservoirs, the ratio of water surface to total volume should be reduced as far as possible. By increasing the depth of the reservoir, rather than the surface area, not only will losses by evaporation be proportionally reduced, but less land will be taken out of production.

Many investigators have studied the possibility of reducing evaporation from a free water surface by the use of surface films that are multimolecular or monomolecular in thickness. The multimolecular films, comprising mixtures of oils and spreaders, were found to be more effective in reducing evaporation than the monomolecular films; but they are thermodynamically unstable and lose very rapidly their ability to reduce evaporation (Mansfield, 1967).

Liquid monomolecular layers, though somewhat less effective in reducing evaporation, were found to be more stable than the multimolecular layers. To be effective,

chemicals that can serve for forming monomolecular layers should be inexpensive, non-poisonous, and stable.

A number of compounds are known that form such a 'monolayer' film on the surface of water in reservoirs, and thereby impede the evaporation of stored water. The molecules of the compounds that form monolayer films have a common characteristic structure: part of the molecule is hydrophilic and part is hydrophobic, repulsing water. The most promising of these substances in field trials up to the present have been fatty alcohols such as hexadecanol and octadecanol, or mixtures of the two. The reduction in evaporation is accomplished without markedly reducing the transfer of oxygen from air to water, or impeding the escape of carbon dioxide from the water. No toxic action was found on micro-organisms, aquatic plants, fish, or other animals (Quintela, 1967). An automatic system for applying the hexadecanol consists of a number of containers spaced around the perimeter of the reservoir, releasing the material through valves. Only those placed upwind operate, and the rate of application is regulated according to wind speed (Langbein, 1962). Although practically insoluble in water because of the extremely small mass involved, a breakdown in the film usually occurs as a result of wave action, dust, and wind.

The best results with monolayers have been obtained on average-sized reservoirs. Experiments in Australia over several years on reservoirs with surfaces of 160 hectares or more, showed overall reductions in evaporation of 15% at a cost of about 3 cents per thousand gallons of water saved (Mansfield, 1967). With appropriate techniques, effective results were obtained on storage areas down to approximately one hectare. For still smaller surfaces, costs were prohibitive.

Intact films on the surface of the water are very effective in reducing evaporation, but they also prevent heat loss from the water covered. As a result, evaporation is increased from any part of the water surface that becomes uncovered.

Wax has been found to be a promising material for reducing evaporation losses from reservoirs. Floating blocks of wax are added to the water; in sunlight they melt and form a flexible, continuous film. Even if the film cracks in cold weather, it is restored when weather becomes warm. The evaporation-suppression efficiency is 85%, and it remains in good condition for a fairly long time (NAS, 1974).

Blocks of lightweight concrete, polystyrene, plastic and other materials, that float on the water, have been under trial for several years. They have the advantage that they do not prevent the loss of heat from the water in the reservoir, as do intact film barriers (NAS, 1974).

No techniques have yet been developed for reducing evaporation losses from very large reservoirs. For the enlarged Aswan Reservoir, the loss by evaporation has been estimated as equivalent to 10% of the annual flow of the Nile (Addison, 1961).

Seepage control

No less important than reducing losses by evaporation, is seepage control, which is usually easier and cheaper to achieve. Conveyance losses and their prevention are

discussed in Ch. 12. Considerable losses are also experienced in the reservoirs themselves, due to soil porosity.

The major factor favouring seepage is a high calcium content of the soil. Calcic clays are porous and crack on drying. An effective treatment is the addition of sodium salts (such as sodium carbonate), provided the soil is at least 30 cm deep, has at least 15% clay, and has the chemical capacity to exchange Ca for Na ions (NAS, 1974).

Small reservoirs can be lined with relative low-cost polyethylene and polypropylene films. Deeper reservoirs need tougher, and more expensive, films of vinyl or reinforced polypropylene. Still more expensive is butyl rubber; but it is tough and durable.

For lining and protecting steep slopes, ferrocement (NTIS, 1973) and soil cement can be used. Soil cement is prepared by blending local soil with a small amount of cement; the mixture is packed into perforated, sausage-shaped plastic tubes. After moistening through the pinholes, the 'sausages' are packed tightly in place and the soil-cement mixture allowed to set (ITDG, 1969).

Salinity of water stored in reservoirs

The salinity of the water flowing into the reservoir may vary considerably in the arid regions, depending on rainfall distribution, the salinity of the watershed, and the changing rates of evaporation.

All water evaporating from reservoirs and lakes must leave a residue of salts which increases the salt content of the stored waters. When the rate of evaporation exceeds the rate of water inflow, the situation may deteriorate at a fairly fast rate, the loss of water being concomitant with increasing salinity.

The salt content of the water in the reservoir will be at its lowest after the main flood-flow during the rainy season, and will reach its highest concentration towards the end of the dry season. The higher the surface:volume ratio is, the greater will be the proportionate loss by evaporation and, as a result, the higher the salt concentration.

Small-scale water storage methods

Water storage is an age-old tradition in arid lands. In many of the arid and semi-arid regions, the only source of water is rainfall. The more sparse and infrequent the rainfall is, the greater have to be the ingenuity and effort to store part of the precipitation for use throughout the year. Cisterns, tanks or ponds, and small reservoirs, have all served for this purpose.

Cisterns

It was only after the invention of a mortar impervious to water, which made it possible to build cisterns for storing rainwater, that the mountainous regions of the

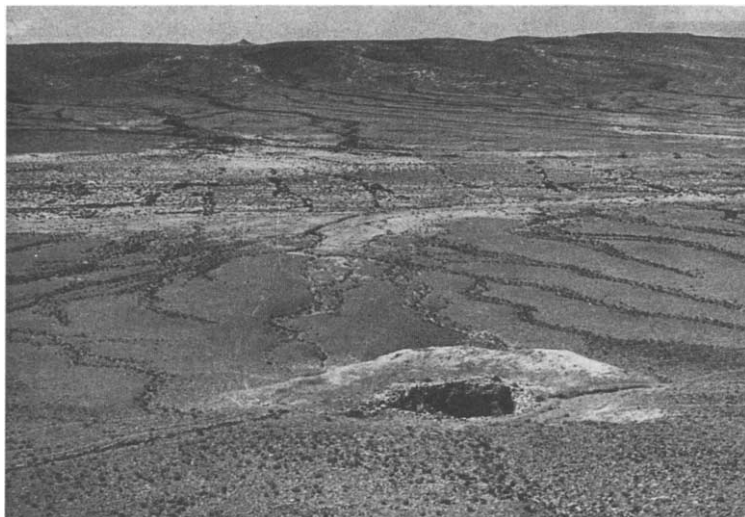


Fig. 4.12. Nabatean cistern in the Negev Desert (end Third Century). Note system of water collection and transfer to cistern; surrounding slopes are cleared of stones to increase run-off. Photo N. Tadmor.

Middle East could be settled. This occurred during the Early Middle Iron Age (Reifenberg, 1953).

Within inhabited areas, the roofs of buildings, paved roads, and courtyards, serve as catchment areas, and the water is led to the narrow opening of a funnel-shaped cistern. As these cisterns are either closed or have a very narrow opening, and their walls are lined with mortar, losses by evaporation and seepage are practically nil.

Outside the built-up areas, cisterns are designed to catch floodwater and are widely dispersed throughout the deserts. Small catchment areas are carefully prepared for this purpose, and channels lead the water to the cistern excavated into the side of the slope. In order to reduce the amount of sediment introduced into the cisterns, in many cases the water first passes through a settling basin. Frequently, cisterns are excavated alongside wadi-beds, and are filled during flash floods.

Some of these cisterns may have quite a considerable capacity, and when a number of them are grouped together, the aggregate quantity of water stored may be quite large (Amiran, 1966).

The Nabatean culture maintained itself in the desert by depending to a large extent on cisterns, cut into the ground and lined with cement. Carefully planned diversion systems led the sporadic run-off from relatively large areas to the cisterns (Fig. 4.12).

Tanks or ponds

Tanks or ponds are holes, excavated in the ground; the earth that is removed is piled



Fig. 4.13. Tank for collecting water during flash floods, that will serve for supplementary irrigation later in the season. Photo Soil Conservation Service, Israel.

in the form of an embankment on three sides. The tanks store run-off water or water from ephemeral streams, filling to ground level. The size of the storage is therefore equal to the size of the excavation, making the tank a very costly way to store water (Geddes, 1964) (Fig. 4.13).

Tanks or ponds are of great importance for watering stock. They enable the grazing of potentially valuable range in regions in which groundwater is not available economically. Whilst they rarely provide an all-year-round water supply, they usually dry out when most of the grazing has already been effectively used. Their main disadvantage is the great loss by evaporation: the drier the season, the greater this loss.

Seepage losses are sometimes controlled by lining the tank or pond with plastic material.

In the past, tanks in India were used for full irrigation of a very small area; the policy of ICRISAT is to encourage use of the run-off water in the tanks for supplemental irrigation on rainfed crops, thereby assuring a crop on most of the land of the watershed area instead of a fully irrigated crop on a fraction of the cropland (Krantz et al., 1978).

El-Swaify et al. (1984) report that Alfisols in semi-arid tropical India, have a high

potential for delivering excess water for storage in tanks. Even improved cropping systems use only 30–45% of the seasonal precipitation, and the remainder either runs off or drains into deeper soil layers; water quantities are sufficient for use for supplemental irrigation.

The major disadvantage is the high seepage rates in the tanks. For efficient storage, the tanks must be constructed in soils having very low permeability, or where the soil has been treated or liners have been installed to reduce seepage.

If a minimum depth of 1 m can be maintained, the tanks can be used for fish production (Gil, 1979).

Small reservoirs

An alternative solution to large dams is a number of micro-dams, starting from the higher parts of small valleys and going down to the bottom of the valley. These create a number of terraces which absorb a large proportion of the water and prevent erosion.

Small reservoirs have been in use in the dry regions of central Asia for ages past. The contents of one of these reservoirs may sometimes suffice for irrigating from a few to several hundreds of hectares (Fig. 4.14).

Underground water reservoirs

Characteristics of groundwater

Definitions

The water that accumulates in a porous zone, situated at a moderate depth below the soil surface, is known as groundwater. The upper surface of the saturated zone is called the water table. Water that is held above the water table by capillary force is called the capillary fringe. The thickness of the capillary fringe, and the amount of water held, depend on soil texture. The lower limit of the saturated zone is the level at which the underlying rock is practically impermeable to water.

During wet periods, or following continuous heavy irrigations, the water table rises, whereas during dry periods, heavy withdrawals will cause the water table to fall. If there is no impervious layer between the groundwater and the soil surface, the former is known as 'phreatic' or 'free' groundwater.

The groundwater reservoir or aquifer consists of saturated porous rock materials that are sufficiently permeable for the water to move through them by gravity and yield water freely to wells (Thomas, 1951).

Importance of groundwater

The groundwater reservoirs are the source of water in wells and springs and the flow



Fig. 4.14. Typical small reservoir in the desert, that supplies drinking water for stock throughout the summer. Photo Soil Conservation Service, Israel.

of streams during rainless periods (Fig. 4.15). Groundwater is, indeed, the main source of water supply in dry regions.

In general, groundwater reservoirs are in dynamic balance with precipitation, evaporation, and drainage to the sea.

The groundwater 'reservoirs' are the source of water in wells and springs and the flow of streams during the rainless periods. The volume of groundwater stored at depths of less than 800 m is generally estimated to be 3000 times as large as that contained in all rivers. The use of groundwater for irrigation has increased steeply in recent years. In India alone, the number of tubewells increased from 20 000 to 500 000 during the decade 1961–71 (Palmer-Jones and Carruthers, 1978).

In contrast to surface supplies, the development of groundwater resources is relatively fast and inexpensive, and is therefore a major factor in the economic development of arid regions.

Depth of groundwater

Groundwater that is relatively near the surface can be used by plants. As a large concentration of roots develops in the capillary fringe above the water table, even a temporary rise in the water table may cause considerable damage by asphyxiating the

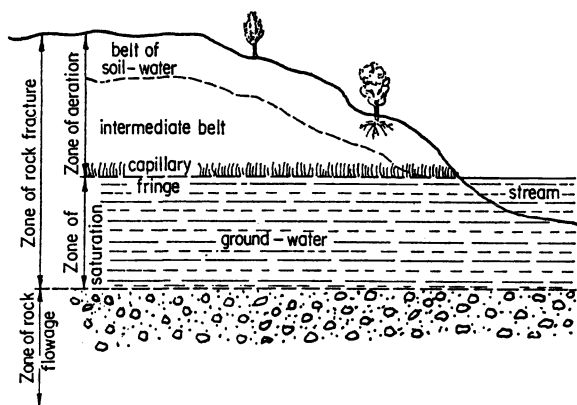


Fig. 4.15. Groundwater zones and belts. By permission of World Farming.

roots. Phreatophytes flourish where the depth of the water table is less than 3 m; the growth of some can, however, still be vigorous when the water table is at a depth of up to 10 m (Robinson, 1967).

However any potential benefits of groundwater near the surface are insignificant in relation to the dangers of high water tables, of which salinization is the most important. This aspect is discussed in detail in Ch. 13.

Natural recharge of underground water reservoirs

Underground water supplies are replenished either by water that reaches the aquifer from a watershed or from precipitation that falls directly on the soil surface over the aquifer. Other sources are excess irrigation water, subterranean streams flowing into the aquifer, seepage from surface streams, and artificial recharge.

The rate at which water derived from a watershed percolates to the underground water reservoir or, alternatively, is lost to the ocean, depends on the nature of the watershed and its slope.

If the watershed is covered by vegetation, water loss will be considerably increased. The nature of the vegetation will influence annual evapotranspiration, and hence the amounts of water which remain available for percolation. If the surface of the watershed is bare rock, the nature of the rock and the degree to which it is fissured will determine the relative amounts of run-off and percolation.

Precipitation in excess of that needed for wetting the soil to field capacity may percolate deeply enough into the soil to be no longer subject to evaporation or accessible to plant roots. Eventually it may become part of the groundwater reservoir.

Normally, the drier a region is, the smaller will be the proportion of natural precipitation that will reach the groundwater reservoir. In regions with less than 200 mm

annual rainfall, rain usually falls on non-saturated ground. Practically no precipitation will infiltrate to a water table – either because the moisture deficiency in the soil is too great, or because the amount of precipitation is too small.

Where the underground waters are replenished by waters that percolate laterally from a humid region, the situation is far more favourable, and there is less danger of excessive withdrawal. Deep boreholes can then tap artesian supplies that have originated at high elevations on the border of the desert.

Quality of groundwaters

The groundwaters in arid regions almost invariably have a high mineral content, but the degree of salinity depends on the nature and structure of the rocks holding the water (Dixey, 1956). Saline waters are frequently associated with a high clay fraction in the water-holding beds, whilst sandstone and grit usually yield water of low salinity (Bosazza, 1954).

Usable and unusable water supplies are frequently found within a short distance of each other. Whilst the water may frequently be acceptable for drinking by livestock and even for human consumption, it is usually far more difficult to find water that is suitable for crop irrigation, for which the quality requirements are far more stringent.

Movement of groundwater

The movement of groundwater is downward and lateral. Its flow is extremely slow – sometimes not more than a few metres per year, and generally not exceeding 3 m per day – except in large underground channels. Underground flow is therefore not a very efficient method of transporting water from the fount of precipitation to the location where it is required (Thomas and Peterson, 1967).

The yield of wells may be more dependent on the rate of movement of the water through an aquifer than on the replenishment of the aquifer. If water is pumped from a well or group of wells more rapidly than it can move through the aquifer towards the wells, the depth of the water table in their immediate vicinity will drop, the cost of pumping will increase, and in extreme cases the wells may be pumped dry even though there is ample water in the aquifer as a whole (Thomas, 1955). The pumping itself may increase the rate of movement in the aquifer by increasing the hydraulic gradient, but this may still be insufficient to balance the rate of withdrawal.

However, by and large, aquifers serve as transmission systems which partially replace, over relatively large distances, surface distribution systems of canals or pipelines, and therefore make possible economies in investment.

Utilization and exploitation of groundwater

Groundwater is a free but limited resource. Because it is free, there is a tendency to exploit it freely, if there are no rules to regulate its use. Because it is limited, it becomes depleted with excessive use. If uncontrolled, the groundwater balance will eventually become disrupted; the farming system may fall to a new equilibrium at

lower levels of production and income (Shah, 1990), or water withdrawal is no longer economically feasible (see below).

In the sandy coastal strips around the Mediterranean, the cumulative effect of growth of tourism, industry and urbanization, and the change from traditional rain-fed agriculture to intensive production of irrigated vegetables and fruits, has resulted in the extraction of excessive amounts of water from aquifers with moderate capacity and the resultant intrusion of sea water (Grove, 1985). A strategy for effective long-term protection against salinity would require a 50% reduction in withdrawal from Israel's main coastal plain aquifer (Galnoor, 1980).

In coastal Saurashtra (Gujarat, India), modern pumping technologies developed in the early 1950's, abetted by supportive government policies that provided subsidies and credit, resulted in a 10–15 fold increase in the amount of water lifted from the coastal aquifer. By the late 1960's many wells started to dry up in the inland areas, and in low-lying areas nearer to the coast, sea-water intrusion into the wells became commonplace (Shah, 1990).

Nabhan and Felger (1985) write: "irrevocable groundwater depletion in arid zones is becoming a common tragedy worldwide". Groundwater extraction in the USA *tripled* in 25 years (1950–75)! (Office of Technology Assessment, 1983). In regions of Arizona, Sonora, Baja California, Mexico, overexploitation of groundwater has led to a continuous lowering of the water table; pumping from a depth of 100 m or more is making the production of water by conventional methods uneconomic and has resulted in hundreds of thousands hectares of farmland being abandoned every year (Foster et al., 1980).

There are two basic approaches to groundwater utilization (Hall, 1957): (a) the *concept of 'safe yield'* is based on the rule that annual groundwater withdrawals should not have undesirable effects, such as sea water intrusion, land subsidence, increased pumping requirements, etc.; (b) the *concept of 'mining' groundwater*: in this case, withdrawal exceeds annual recharge, sometimes considerably.

Groundwaters used according to the concept of 'safe yield'

When an underground water reservoir exists in an arid region, it provides a more reliable and regular water supply than do surface waters of local origin. It can be drawn on throughout the year, and may even be overdrawn for a period of one or two years of drought. Where underground water supplies in arid regions are dependent on local precipitation, the stored water has accumulated over many generations. It is not, however, inexhaustible. Withdrawal of water by pumping may exceed the annual restoration capacity of the aquifer to such a degree that the level of the aquifer falls and the wells become less productive. The less the precipitation occurring in a given season, the greater will be the effect of withdrawal of water in order to maintain an adequate irrigation supply to the crops.

The 'point of no return' may be reached, when the water level becomes so low that pumping costs become prohibitive, or when sea water intrudes into the aquifer as

frequently occurs in coastal areas. Even when overwithdrawal does not lead to exhaustion, it almost inevitably does lead to an increase in salinity. All such withdrawal exceeding annual recharge is known as 'mining' of groundwater.

'Mining' groundwater

Some groundwater reservoirs are replenished only occasionally: this is the case in many deserts, after a heavy rainstorm which may occur once in several years (Thomas, 1951).

Some aquifers are completely sealed off by layers of impervious material, such as clay, so that replenishment is impossible.

In some cases the basins are so great, and have such huge reserves, that a very long period of time is necessary before any assessment can be made of what constitutes a safe rate of withdrawal. The rate of flow of the springs of Djerid in Tunisia has remained constant over a period of 50 years, notwithstanding the fluctuations in the water supply to the aquifer from which they are derived – indicating an enormous reserve which can absorb annual fluctuations (Tixeront, 1956). A similar situation occurs in deserts where waters have accumulated underground, during a more humid period of the recent geological past; these waters are no longer replenished and are therefore called 'fossil' water.

Aquifers of this type are found beneath deserts in northern Mexico, southwestern United States, north Africa, eastern Saudi Arabia, the Sinai, the Negev of Israel, and southwest Asia. Development of some of these aquifers is proceeding in a number of countries. Withdrawing water from these aquifers is definitely a mining operation.

A justification for 'mining' water is when it is first used in order to develop and strengthen the local economy, so that at a later stage it will be possible to bring in water from other regions or to develop additional water resources in the region. This really constitutes a 'planned overdraft'.

Withdrawal of groundwater

Wells and boreholes

Normally, the term 'well' is reserved for structures that are more than one metre in diameter. Boreholes, or tubewells, are bored by a drill, and consist of perforated tubes, of relatively small diameter, which reach into the lower aquifers.

Wells. Since time immemorial, wells dug by hand to reach the zone of saturation have supplied water to the inhabitants of arid regions. In many deserts, localities carry the names of the well or wells found on the spot. Most of the wells in arid regions were developed in the earliest times of civilization and continue to be used, without much improvement, by the present inhabitants of the area.

A characteristic feature of many wells in desert regions is the presence of a thin

layer of good water (usually not more than 1–2 m deep) overlying water with a far greater degree of salinity. This occurs when newly percolated rain reaches the water table and does not mix with the body of saline water (Shotton, 1954). If the inflow of fresh water were greater, it would not remain unmixed with the salt water (Dixey, 1956); such wells, however, have only a very small yield, and are of little or no significance for the irrigation of crops. Their importance lies in making possible the grazing of desert areas, and therefore cannot be overestimated.

Wells have, however, also served as a source of irrigation water since prehistoric times. The depth of the water table in these wells generally ranged from 1–30 m. Primitive devices, activated by hand or by animal power, served to lift the water.

Interest in wells is reviving; instead of the former crude holes in the ground, that were breeding grounds for parasitic and bacteriological diseases, modern materials and equipment can dig wells that are soundly engineered, hygienic and reliable sources of water. Wells are inexpensive, easy to construct and to maintain. They can also serve as storage for water (cf. p. 158) (NAS, 1974).

Wells cannot tap groundwater that is deeper than 20–30 m, and their water output is relatively low. Their main advantages are for use where aquifers are shallow and low-yielding, and for inaccessible regions where transport of drilling equipment is difficult (NAS, 1974).

Boreholes or tubewells. The development of large-scale well irrigation was made possible by a succession of technical innovations: these included the wind-driven pump, the gasoline-engine pump, mechanical deep-well drilling equipment, and the submerged centrifugal pump. However, it was the deep-well turbine pump which made it possible to lift water economically from quite considerable depths (Gregor, 1959).

Tubewells have a number of advantages over other sources of water supply: they are relatively easy to develop and their number can be increased rapidly in response to requirements; when they are situated on the land to be irrigated, the distribution system is short and inexpensive; by their use the farmers have improved control of the water supply; health hazards are less than from surface water, provided the necessary precautions to avoid contamination are taken; and the danger of a rise in water table with associated drainage problems is avoided.

The main disadvantages of tubewells are the fairly high capital and recurrent costs, and the possibility of overexploitation (Palmer-Jones and Carruthers, 1978).

In general, groundwater reservoirs are in dynamic balance with precipitation, evaporation, and drainage to the sea. However, because tubewells belonging to different owners tap the same aquifer, overexploitation is a frequent occurrence, resulting in a lowering of the water table and, in more extreme cases, in irreversible damage to the aquifer as a result of the intrusion of saltwater or land subsidence.

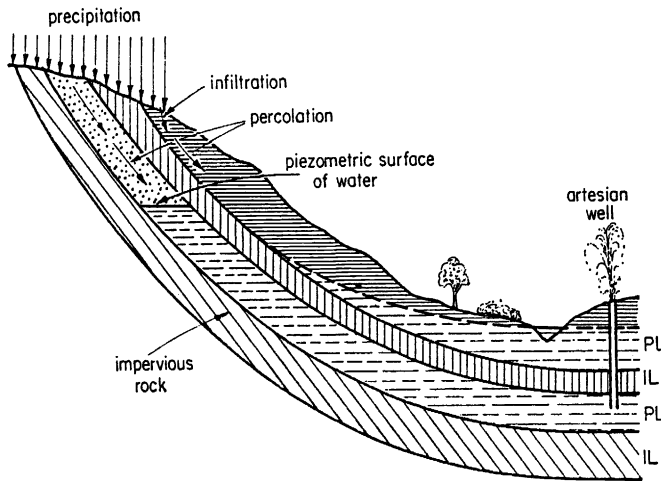


Fig. 4.16. Artesian groundwater and well. PL = pervious layer; IL = impervious layer. By permission of World Farming.

Artesian wells

When an aquifer that originates at a high elevation is confined between two impervious layers, hydrostatic pressure is engendered which may be sufficient to cause the water to rise in wells located at a lower elevation. Such water is known as artesian water (Figure 4.16).

Artesian wells are an important source of water supply in many arid regions. Important examples are the great artesian basins of Australia and the deep artesian wells of Tunis and Tripolitania. The depressions of Kharga and Dakhla in Egypt receive good water from a geological structure of Nubian sandstone, which outcrops in the Sudan, over 1000 km to their south (Shotton, 1954).

Shotton (1954) lists the following conditions for artesian supplies in the desert to be available in large and useful amounts:

- (1) the aquifer has to outcrop in a region of adequate rainfall;
- (2) the aquifer should have high permeability beneath the desert, so that water movement is sufficient to make high water-withdrawal rates possible;
- (3) the water should not be contaminated by saline water on its way from the intake area; and
- (4) water withdrawal should be balanced by intake.

In the aforementioned depressions of Kharga and Dakhla, artesian water of good quality was abundant, but increase in the number of boreholes, and their depth, were out of proportion to the renewal rate, so that water pressure has dropped continuously.

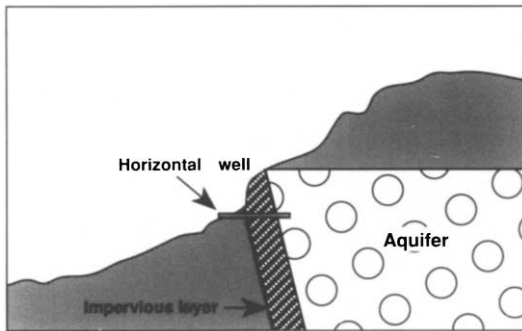


Fig. 4.17. Schematic representation of a horizontal well.

In the Great Artesian basin of Australia, much of the water becomes salinized on the way from the intake area to the basin, and cannot be used for irrigation. There appears to be no suitable geological structure for artesian supply in the Great Australian Desert (Shotton, 1954).

In general, the development of artesian wells requires costly drilling, frequently to depths of 1000 to 2000 m or even more. The limitation may therefore be not lack of water, but its high cost (Dixey, 1964).

Horizontal wells

The horizontal well, or cased spring system, is used to tap a water supply trapped in a hill- or mountainside. A horizontal boring rig is used to drill a hole and install steel pipecasing (Fig. 4.17). Promising indications for installing horizontal wells are springs, seeps, traces of water or phreatophytes.

Maintenance costs of horizontal wells are low, no pumps are needed, and the water supply is protected from contamination (NAS, 1974).

*Qanats**

When an aquifer in the plainland at the foot of a mountain is wide and shallow, the conventional circular well is not efficient for tapping this supply. An underground system of infiltration tunnels for taking water from these aquifers to the land to be irrigated was developed thousands of years ago. Whilst their origin is obscure, these underground aqueducts were already used by the Persians in prehistoric times, and occur in many countries of the Near East.

A qanat is established by digging a number of vertical shafts to the watertable, and then excavating between them a gallery with a gently sloping flow (Fig. 4.18).

*Called 'karez' in Persia, 'foggaras' in North Africa, 'puquio' or 'socavones' in South America; it signifies a subterranean canal in Arabic

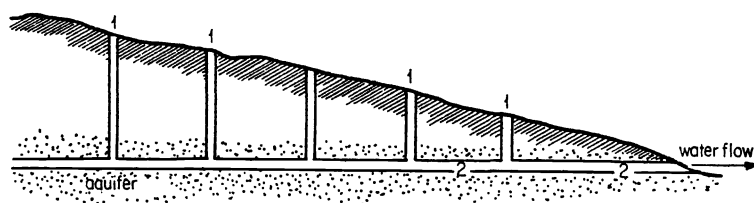


Fig. 4.18. Schematic representation of qanat system. 1 = access shafts; 2 = water-collecting gallery with slight slope.

Water collects in the gallery and flows by gravity until it emerges into the open air. The distance which the water may be transported by the qanats may vary from several hundred metres to a number of kilometres (Dixey, 1966). In Iran there exist thousands of qanats, which are the sole water supply of numerous villages and supply irrigation water for extensive areas (Cressey, 1958).

According to Chinese records, a system of qanats was already operating in the Shansi Province during the Han era (about 200 B.C.). A vast network of qanats is still in operation in the region of the Siang-Kiang in China, where it forms the most important irrigation system, with a total of 1500 underground canals irrigating in all some 20 000 ha (Kovda, 1961). Extensive qanat systems exist also in North Africa.

A system similar to the qanats of Iran, called 'puquio', is found in the central Andes (Kobori, 1964). Opinions are divided as to whether the puquio were invented by the Indians, independently of the Old World (C. Troll, as cited by Kobori, 1964), or were introduced by the Spaniards (Amiran, 1966).

Qanats have the advantage of flowing both day and night, without requiring a source of energy; since the water is derived from high up in the alluvial fan, it is fresh and cool, and pollution is avoided. Losses by evaporation are prevented, but much water may be lost by seepage.

Water yields of qanats vary widely, depending on groundwater characteristics, the porosity of the soil, and the season. Qanats that derive their water from a stable groundwater source may provide an almost constant flow throughout the year, whilst the supply from others may be intermittent and dry up completely in the dry season (Cressey, 1958).

The water obtainable from qanats varies; in a study of 200 qanats in a plain southeast of Teheran, the largest yield measured was 270 liters/second and the lowest, only 1 liter/second (Wulff, 1968).

Construction of qanats is a specialized trade, and has frequently served as a family occupation for generations. Enormous amounts of hand labour are involved in their construction and maintenance. New qanats are only seldom built, but many old ones are still in use. In Iran, about 40 000 qanats supply more than one-third of the country's water (NAS, 1974).

The average life of a quanat system is between 100 and 150 years, the underground channels becoming gradually silted up. When the flow of water becomes too sluggish for effective use, a new system has to be built alongside the old one, and frequently five or more parallel lines of old wells may be discerned. A recent innovation adopted in Iran is to dig a well to below the water table, and then bore out horizontal galleries, using the traditional excavation methods of the quanat builders. A centrifugal pump is installed in the well-shaft to pump the water collected by the horizontal shafts (NAS, 1974).

Chotts and sabhas

In some desert regions run-off water concentrates in depressions which form closed underground basins, usually filled with a very fine silt. These depressions, called chotts or sabhas, are usually covered by patches of typical and abundant halophytic vegetation. The continuous evapotranspiration results in a high salt content of the water, frequently shown by the salt incrustations that form on the surface of the soil. Tixeront (1956) states that it is not uncommon to find layers of less salty waters below the salt-saturated ones near the soil surface.

Drainage lines

The sparse vegetation of desert regions, the surface dryness, and the occasional torrential rainfall, cause a high rate of run-off, which concentrates between the catchment areas into the dry riverbeds that are the typical drainage lines of desert countries. Along these drainage lines, water may accumulate in shallow underground pools that can easily be tapped by water holes or wells. Typical are the meandering, narrow strips of vegetation which mark the location of the drainage lines in the desert and are in contrast with the barren countryside.

Subsurface flow in dry riverbeds

In all arid regions there are riverbeds* which carry occasional torrents, but which are dry during most months of the year. In some of these, water continues to flow under the surface even when the surface flow has ceased. Where special conditions at the site make it possible to construct a subsurface dam, underflow may be held up to form a subsurface reservoir that may supply water throughout the year. The sudden appearance of a considerable flow of water from an apparently dry streambed in the middle of the desert is indeed a striking sight! Unfortunately, it is usually difficult and even rare to find a section of the streambed that is suitable for building a dam, the requirement being a site where the sides and floor of the streambed are sufficiently impervious (Dixey, 1956).

*Called 'wadis' in the Near East, 'oueds' in North Africa, and 'arroyos' in America.

Recharge of groundwater – underground storage

In the arid regions, the proportion of rainfall reaching the groundwater is very small, and usually does not exceed 5% (Dixey, 1956). Therefore, the artificial recharge of groundwater is assuming increasing importance. As has been mentioned previously, the excessive withdrawal of water from the underground reservoir is a common feature in irrigated regions; not only do increased pumping costs and increased salinity result, but the very future of the water supply may be endangered by the intrusion of salt water into the aquifer. On the other hand, experience has shown that, in arid regions, groundwater storage has many advantages over surface reservoirs: it is not subject to losses by evaporation, and annual fluctuations in precipitation do not have such a marked and immediate effect as is the case in surface reservoirs.

In the semi-arid regions, in which a period with adequate rainfall alternates with an absolutely dry period, underground water supplies can help to offset the variability of the rainfall and to prolong the growing season.

Preconditions for successful recharge are an effective absorption surface and a suitable aquifer (Dixey, 1956). Surplus water from springs or streams, at a time when they are not required for irrigation, can be used for replenishing groundwater. Floodwaters can also be used for recharge, although the sediments which they carry may cause difficulties by reducing the infiltration capacity of the soil. The silt may have to be removed from the water before it is led to the infiltration basins overlying the groundwater to be recharged.

The building of dams and weirs in streams increases the infiltration of water along the channels of the streams, replenishing water supplies to the wells and boreholes in the vicinity (Dixey, 1956).

When flow channels reach a valley floor they usually spread out, depositing the coarsest material first – thereby forming, in time, an extensive fan of coarse sediments which have a high percolation rate. By establishing a system of relatively simple checks and diversion dams, a proportion of the streamflow is forced underground, whence it reaches the aquifer.

The main disadvantage of this method is that the water is at a great distance from the withdrawal region, and therefore recharge is not very effective at the site where the water is needed (Hall, 1957).

Water spreading

This consists in diverting excess water, from whatever source it may be available, and spreading it over porous ground overlying the aquifer (Mitchelson and Muckel, 1937).

In principle, the methods used for water spreading approximate those used for surface irrigation, the main difference being in the objectives: in the former, the objective is to encourage deep percolation into the underground basin; in the latter it is desired to confine the applied water to the root zone. One of the difficulties experi-

enced in recharging an aquifer is surface clogging, due to the suspended solids in the recharge water and to microbial growth. The former is the most important factor when floodwaters are used for recharge, the latter when municipal wastes are used for this purpose.

When the basins remain dry for a substantial time, the surface soil again becomes permeable, and, after a period of rest, infiltration rates are considerably improved.

The main principles to be followed in water spreading are (Schiff and Muckel, 1967):

- (a) to free the water from silt as far as possible;
 - (b) to pond the water to relatively high levels in order to increase hydraulic conductivity;
 - (c) rotational flooding, so as to enable the land to dry out periodically, in order to recover the original infiltration rate; and
 - (d) to maintain and improve, as far as possible, the structure of the surface soil.
- Maintaining the original plant cover, or, alternatively, scraping or hoeing after surface drying, improves infiltration.

Use of bores or wells

In areas in which an unsuitable soil surface, or an impervious layer under the soil surface, makes the methods used for surface spreading impracticable, special bores can be drilled, or old wells used, in order to replenish the aquifer. Percolation rates are usually high, but the limited area precludes use of large amounts of water. Active wells are sometimes used for recharge purposes, by reversing the flow of the water. This is not a method to be recommended, because even small amounts of silt may seal the walls and bottom of the well and put it out of action. It is practically impossible to clear the sealing material from the walls of the well. Bacterial contamination of the domestic water supply is also a possibility. When clear or filtered and chlorinated water can be used, this recharge method can occasionally be used on a small scale (Hall, 1957).

Recharge wells have been successful in some areas and have failed in others, and much has still to be learned in improving the techniques of artificial recharge (Thomas, 1951).

A new approach to groundwater recharge is the intentional use of excessive amounts of water during irrigation of crops in the off-irrigation period, so that the surplus will be added to the groundwater.

Some of the methods of groundwater recharge described above are already being used on a large scale, e.g., in the USA and in Israel. For some regions, groundwater recharge is the only possible method of water storage; for others, where surface storage is also possible, underground storage may have obvious advantages – less costly works being required, losses from evaporation being reduced, etc.

It is generally accepted that most of the water stored underground is recover-

able (Mitchelson and Muckel, 1937); such water is recovered by pumping from wells.

Unconventional water resources

Water reuse

Since the 1960's, considerable attention has been given to recycling of treated wastewater as an additional source of water for irrigation of certain crops, groundwater recharge and industrial use. At the same time, pollution of streams, lakes and the aquifer is reduced. The major concerns in the reuse of sewage is the possible survival of pathogenic micro-organisms, and in the case of industrial wastes the main problem is the presence of toxic materials (UN, 1985). Before reuse is possible, treatment for quality improvement is essential. The techniques of improvement vary according to the nature of the contamination and the purpose for which the water is to be used.

Recovery of excess surface irrigation water

By constructing an irrigation return-water system at the low end of irrigated fields, it is possible to reuse water at relatively low cost. For this purpose, a reservoir or sump is constructed which collects all surplus irrigation water, which is then repumped to the head of the field for reuse (Hagan et al., 1967). However, the return of drainage waters to the main stream causes an increase in the total concentration of soluble salts, and in the proportion and quantity of sodium and chloride whilst calcium, magnesium, sulphate, and bicarbonate, are reduced by precipitation.

For example, the salt content of the Colorado River, as it flows into Mexico, has increased alarmingly, as a consequence of the pumping of subsoil saline waters from irrigated areas, which are then diverted into the river (Anaya, 1967).

Use of wastewater

Wastewater can be used for irrigation, for industry, for recharge of groundwater, and in special cases, properly treated wastewater has been used for municipal supply. In all these cases, more good-quality water, suitable for human consumption, will be freed.

The amounts of water used for waste disposal in developed countries are enormous. It has been reported that more than 80% of the total freshwater used in the United States is for waste disposal (UNEP/FAO, 1977) – hence the justification for making these effluents safe for reuse.

Use of effluents from sewage treatment processes. Untreated sewage has been traditionally used for irrigation in the Far East and southeastern Asia, without any restrictions. In developed countries, the use of raw sewage is generally not allowed for

irrigation of any kind, because of the risk of direct infection of the workers, transmission of disease by flies and other vectors, and contamination of the foods produced. Even partially treated effluent can present real health risks, not only with fruit and vegetables that are eaten uncooked but also with roots and tubers that are cooked. In the latter case it is the housewife, the kitchen and the appliances that may be contaminated.

Sewage treatment. Biological treatment processes remove a substantial portion of the organic matter, and, in their course, many pathogenic organisms may be destroyed – though the water may still remain dangerous from the point of view of human health. In general, even a well-run biological sewage treatment plant will not remove more than 90% of the pathogenic organisms present in the raw sewage (Shuval, 1967).

The remaining hazard from viruses after advanced waste treatment is not known. The prevailing view is that present known treatment processes remove the hazard only if carefully controlled (Malina and Sagic, 1974).

A large number of processes have been investigated as to their technical and economic feasibility for the purification of sewage. A few of these techniques are: adsorption on activated carbon for the removal of colloidal and suspended solids (including the soluble, refractory organics), electrodialysis for removing the added inorganic salts, a foam separation process for removing detergents, and chemical oxidation for the destruction of organic molecules in dilute solution (Weinberger and Stephan, 1967).

Hall (1981) suggests water weed production as a solution to sewage disposal. "Water weeds thrive on sewage, they clean the water effectively, and grow rapidly in the process". Anaerobic fermentation of the biomass produced would appear to be the most appropriate technology for processing into feed, fertilizer, and fuel.

The author suggests that water hyacinth could be excellent for this purpose, because of its prolific growth rate; the floating plants are also easy to harvest. Several countries use water hyacinth for the production of biogas.

Algal ponds that incorporate organic wastes are a promising additional solution in the sunnier parts of the world for liquid waste disposal.

In view of the health hazards involved, many countries limit the use of reclaimed sewage waters to certain crops not used for human consumption, or to those consumed only after processing and/or cooking. Methods of irrigation which prevent direct contact between the marketable product and the reclaimed sewage, such as furrow irrigation, present less risk of contamination than do other methods, such as overhead irrigation (Shuval, 1967).

Use of municipal wastewater for irrigation. The use of municipal wastewater for irrigating land in the proximity of the city is probably the most effective and economic way to solve what would otherwise be a costly and difficult disposal problem.

Whilst Mexico City reportedly supplies vast amounts of untreated sewage for irrigating lands around the city, some biological treatment should precede land application (NAS, 1974).

A model of the beneficial use of wastewater is the Melbourne Sewerage Farm at Werribee (Australia), that has been in use since 1892. The water from the city of 2 million inhabitants, is used to irrigate a formerly barren, windswept plain; irrigated pastures are used for grazing 15 000 head of cattle through the year and 40–50 thousand sheep are fattened during spring and summer. No higher than usual incidence of disease among farm employees was recorded; the condemnation rate of cattle and sheep carcasses was no higher than that of the surrounding area (APWA, 1973).

By contrast, workers on less well operated sewage irrigation projects in India have been found to have an abnormally high infestation by parasites (NAS, 1974).

Partially treated effluents may be used with little risk for crops such as cotton, seed crops, tree nurseries, etc. They also have the advantage of providing plant nutrients and thereby reducing the rates of fertilizers required.

Municipal wastewater can be used for irrigation only during the dry season. During the rainy season, it can serve for groundwater recharge. This has the considerable advantage of improving the sanitary condition of the water, by the removal of most of the micro-organisms if the water is withdrawn from the aquifer at a reasonable distance from the location of the recharge area; it may even become suitable for drinking purposes. Any undesirable materials contained in the effluent will be diluted by the water already present in the aquifer (Amramy, 1967).

After adequate treatment, *municipal wastewater* can be an important source of water for irrigation. The main characteristics of municipal wastewaters are the presence of disease-causing organisms, and of contaminants from home and industry – which include toxic materials, salts, organic compounds, detergents, etc.

Irrigation with treated municipal waste water is carried out in Mexico, for irrigating lucerne, maize and wheat; in Puerto Rico and Hawaii for sugarcane; and in Israel for lucerne and cotton.

A major problem is the need for storage capacity or alternate use (such as recharging the aquifer) during periods when irrigation is not necessary.

Under certain circumstances, there may be economic justification to use advanced technological processes that have been developed; these are based on physical, biological and chemical principles that make treated effluents safe for irrigation, without restriction, for all crops. Such a process typically consists of a number of stages.

In the first stage, biological treatment in oxidation ponds removes settleable solids such as sand, scum and some suspended solids from the raw wastewater. The turbid liquid obtained is treated with lime, which flocculates most of the suspended solids that consists mainly of organic matter. The lime-treated effluent is then maintained in open ponds, where most of the remaining solids settle and most of the nitrogen is released into the atmosphere in the form of ammonia (Idelovitch, 1977).

The use of the treated effluent for groundwater recharge, rather than immediate

reuse, provides a considerable safety factor, because of reduction in the number of micro-organisms and dilution.

Soils in the dry regions are much better suited for groundwater recharge with treated waste water than soils in humid zones. Because of the higher evaporation rate and higher temperatures, 37 times more water can be renovated per unit land in Arizona than in Wisconsin (Fetter and Holzmacher, 1974).

In order to avoid contamination of groundwater by pathogenic micro-organisms, a sufficient distance should be allowed between the land treatment facility and the point where groundwater is tapped for human consumption.

Certain kinds and sources of pollution are becoming increasingly important: these include refractory organic materials, radioactive wastes and inorganic salts. Many problems are therefore involved in the use of effluents.

The system recommended for reuse schemes in developing countries is the use of ponds (UN, 1985). The method is simple, reliable and has low energy requirements, as contrasted with the complex technology of advanced treatment plants. Ponds function in a way similar to natural systems. The ponds are used for sewage treatment, fish production and irrigation in many developing countries in Asia, Africa and Latin America (Reid, 1982).

The treatment and reuse of wastewater for drinking is not recommended because of the high costs of development, treatment and transport, as well as the inherent health danger. The most appropriate uses of treated wastewater in the developing countries are: irrigation of suitable crops, groundwater recharge, possibly livestock watering and certain industrial uses (UN, 1985).

Unfortunately, the scope for the reuse of wastewater in the developing countries appears to be fairly limited, mainly because most of these countries still do not have centralized sewage systems.

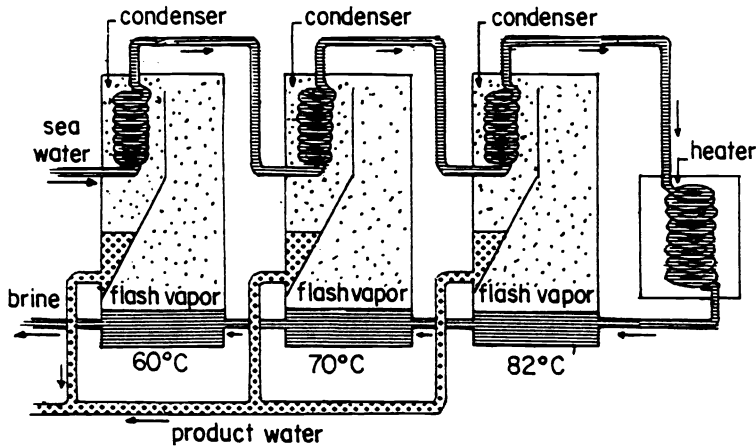
More than 20 countries in Africa, Asia, and Latin America are using wastewater treatment systems. However, most of these report that they have encountered difficulties due to inadequate maintenance, heavy rainfall, and excessive amounts of organic matter in the effluents (Reid, 1982).

Desalination

Practically untapped major sources of water for arid lands are sea water and brackish lake and groundwater. Methods of desalination which would provide fresh water from these sources at an economical cost, would solve the problem of water for many areas in which no other solution is in sight.

Desalination methods

A number of methods have been developed to produce fresh water from saline water.



These conversion processes are based on distillation, passage through membranes, freezing, humidification, and chemical processes.

The methods that are most advanced technologically for converting water in the quantities required for irrigation are based on: (a) distillation and reverse osmosis for conversion of water, such as sea water, with very high salt content (35 000 ppm total soluble salts (TSS) and more), or (b) reverse osmosis and electrodialysis for converting brackish water (3000 to 4000 ppm TSS) into water that can be used for irrigation.

Distillation. The concept of distillation for producing fresh water has been known, and applied on a small scale, for centuries. In principle, such distillation consists in applying heat to salt water to vaporize the water, and then removing the heat in order to condense the steam produced. Increased efficiency in the process is achieved by transferring the heat from the vapour that is being condensed to the water that is being heated – thereby recovering part of the free energy for recycling. As the energy requirements for this method are almost independent of the amount of salts in solution in the ‘raw’ water, distillation is most suitable for water with a very high salt content, such as sea water.

From the basic principle of distillation have been developed a number of processes, of which the most promising at present is multistage flash distillation (Fig. 4.19). This process is based on the fact that, the lower the pressure, the lower the temperature at which water starts boiling. As the name indicates, the water is converted in a number of stages.

Heated sea water is introduced into a chamber in which the pressure is sufficiently low to cause part of the water to boil immediately, and ‘flash’ into steam. As a result, the temperature of the remaining water is lowered. It flows into the next chamber,

where pressure is lower than in the first chamber, so that part of the water is again 'flashed' into vapour, even though its temperature has been reduced. This process is repeated a number of times, in chambers with progressively lower pressures.

The vapour is condensed by coming in contact, in a heat exchanger, with the incoming salt water, so that part of the heat is transferred from the steam to the sea water. The remaining brine, which is returned to the sea, is only slightly warmer than the incoming sea water, as approximately 90% of the heat energy has been recovered (US Department of the Interior, 1966).

The first commercial multistage flash seawater evaporator was built in 1960, and no significant development has occurred since then in the methods based on distillation (UN, 1985). Most large distillation plants are now installed in conjunction with power plants and use waste heat from the latter for the evaporation process. The dual-purpose plants drastically reduce the amount of fuel required, compared to two separate plants producing electricity and desalinated water, respectively. Savings can add up to 25%. Dual-purpose plants are widely used in North Africa and the Middle East (UN, 1985).

Membrane processes. In brackish water desalting, the major advances have been in improved reverse osmosis technology and the development of the electrodialysis reversal process.

The basic unit of a conversion plant employing electrodialysis is an electrolytic cell containing two different ion-selective membranes – one allowing the passage of cations and the other that of the anions (Fig. 4.20). When electricity is applied, the positively charged cations migrate towards the cathode, passing through one membrane, and the negative anions migrate towards the anode, passing through the other membrane. Fresh water remains between the two membranes.

Actually, an electrodialysis cell is made up of many alternating cation- and anion-permeable membranes which form channels for the flow of the water. The salt content of the water is depleted and enriched in alternating channels when electricity is turned on in the end electrodes.

In the electrodialysis reversal process, the polarity and flow in the stacks is reversed at regular intervals, thereby reducing scaling problems. In reverse osmosis, pressure is extended on the salt water, forcing fresh water to diffuse through the semi-permeable membrane in the opposite direction to normal osmotic flow.

In the methods based on passage through membranes, the amount of electric current that is required is proportional to the amount of salts in the water to be converted. For this reason these methods are mainly used for removing part of the salts of brackish water, taking the water to a level safe for irrigation or for drinking. However, since 1978, the development of membranes which can be operated at relatively high pressures has made reverse osmosis for sea water desalination a feasible alternative to distillation (UN, 1985).

A special application of electrodialysis is the demineralization of brackish water

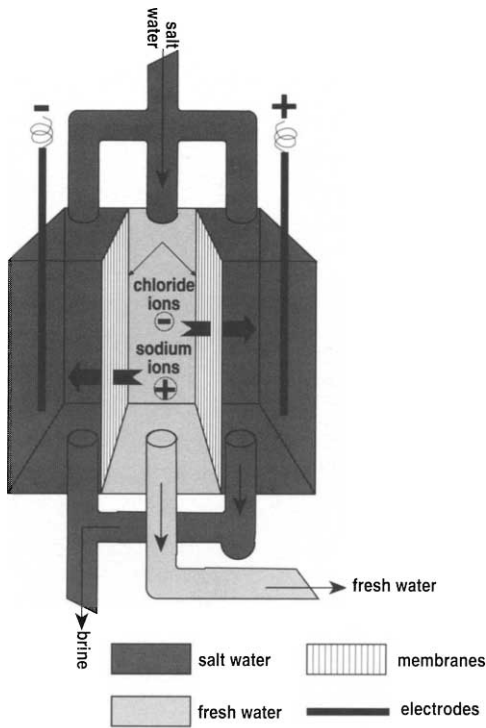


Fig. 4.20. Scheme of an electrodialysis cell. By courtesy of the US Department of the Interior.

that is being pumped in order to prevent its intrusion into a fresh-water zone, thereby achieving two objectives at the same time (UN, 1964).

The principle of reverse osmosis is illustrated in Fig. 4.21a and a diagram of the actual process is shown in Fig. 4.21b. The salt water is first pumped through a filter to remove solid particles and is then raised to operating pressure by a second pump before being introduced into the desalination unit. Part of the water permeates the membrane and is collected at the bottom of the unit, whilst the remaining brine is discharged at the top of the unit.

Multipurpose plants

When generating electric power, the steam that has activated a steam turbine which is driving an electric generator, still contains a considerable amount of heat energy. By using the residual heat of the exhaust steam as a source of energy for a distillation conversion process, the cost of energy for desalination is reduced considerably.

A conventional steam turbine power plant, combined with a multistage flash evaporator distillation plant, gives the greatest promise for reducing the production costs of desalinated water (Sporn, 1966). Tripurpose plants are also envisaged. In Kuwait,

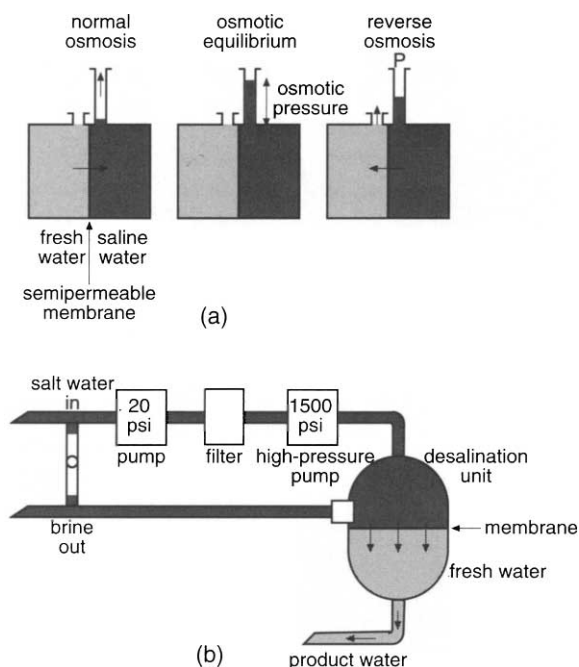


Fig. 4.21. Schematic representation of the reverse osmosis process. (a) Principles of reverse osmosis; (b) schematic diagram of the process. By courtesy of the US Department of the Interior.

i.e., in addition to desalination and the production of power, caustic soda, salt, chlorine, and hydrochloric acid, are all extracted from the residual brine (UN, 1967). The brine could also be a source of magnesium and potash (US Department of the Interior, 1966).

Further expected developments

The use of desalination plants is spreading rapidly in those countries that have practically exhausted the potential of their conventional water supplies.

In 1950, the worldwide capacity of desalination plants amounted to 10 000 m³ per day. By 1984, following the improvements in technology and economies of scale, desalination capacity in the world had increased to 7½ million m³ per day. The steep increase in energy costs made it impossible to produce desalinated water at the previous target price of US \$0.35 per m³, but did create an enormous market in the oil-rich but water-deficient countries of the Middle East and North Africa (UN, 1985), which by 1981 accounted for about 65% of the total world desalination capacity (El-Ramley and Longdon, 1981).

An installation with a capacity of over one million m³ per day was completed in Saudi Arabia in the early 1980's. Without the water supplied by the desalination

plants, sustained economic growth in the country would have been impossible. Other countries which depend on desalination to complement their water resources are: Kuwait, the United Emirates, Qatar, Bahrein, Iran, Lybia, Oman, Algeria, Israel, countries of the Caribbean, Malta and Hong Kong (UN, 1985). The reverse osmosis process has proven to be a reliable and viable means of desalinating both brackish and sea water; by 1981, about $1\frac{1}{2}$ million m³ per day were being produced by this method in 63 countries (UN, 1985).

Up to the present, the water obtained from desalination is mainly used for industrial purposes, for promoting tourism and for urban water supplies. The quantities used for agricultural production are mainly limited to controlled conditions, such as in greenhouses, for high-value crops.

The rapid expansion of water desalination stimulates research towards finding methods of reducing costs and improving reliability, so that eventually water may be produced that can be used economically in agricultural production.

However, in comparison to the cost of most conventional water sources, desalinated water is still considerably more expensive. The process is energy-intensive and improvements in equipment and efficiency have been offset by increases in energy costs. Notwithstanding the costs, the economic conditions justifying desalination already exist in many water-short areas (UN, 1985).

For desalinating plants that are situated inland, an acceptable brine disposal method that is adapted to local conditions must be available, with the costs of brine disposal included in cost estimates. In Japan, salt is produced from the brine, which is concentrated in ponds, with the water removed by solar evaporation.

Apart from costs, the major problem for developing countries wishing to use the distillation method of desalinization is the complexity of operation and maintenance. By contrast, the proven reliability of the electrodialysis process makes it attractive for desalting brackish water. One important advantage of the reverse osmosis process is the possibility of installing small modular units, to which additional capacity can be added when needed.

In very arid areas and remote rural communities, desalinization can provide a source of clean drinking water; the improved public health and the freeing of the women from carrying water over long distances are advantages that are difficult to quantify. However, even for drinking water, the costs of desalination are still beyond the means of most rural communities in the poorer developing countries. Desalination has become a feasible option for middle-income and oil-exporting developing countries (UN, 1985).

Increasing precipitation

The presence of clouds alone does not ensure precipitation. The droplets of moisture which constitute the cloud are frequently too small to reach the weight required for them to fall earthwards as precipitation. For this reason only a small fraction, usually

less than 10%, of the moisture in the atmosphere reaches the ground as precipitation (Schleusener and Grant, 1967).

A number of methods have been developed for artificially stimulating precipitation. They are all based on seeding the cloud with nuclei, on which the moisture will condense. Seeding suitable clouds with dry ice (solid carbon dioxide) reduces their temperature and triggers the process of formation of ice crystals.

Another approach, artificial nucleation, is based on the fact that dust or other particles may serve as nuclei of condensation, enabling rain droplets to form at temperatures that are somewhat above those normally required for ice crystal formation. In particular, crystals of silver iodide are known to be effective as an ice-nucleating agent at a temperature of -5°C , the threshold temperature of silver iodide (Neuman, 1967).

This technique can produce additional precipitation either by initiating precipitation in clouds in which lack of ice crystals prevents the process or by increasing precipitation efficiency in already precipitating clouds by the introduction of ice nuclei in warmer parts of the cloud, where they would not naturally form.

Seeding of clouds can therefore be effective in causing rainfall only when conditions are not too different from those under which the precipitation would occur naturally, at which time seeding may 'tip the balance' – hence the difficulty of deciding unequivocally whether cloud seeding has been instrumental in causing rainfall or not. Also, improper seeding, overseeding or seeding during conditions either too warm or too cold can have negative results. As a result of extensive research, sufficient information is now available to make it possible to define cloud conditions suitable for the successful implementation of seeding techniques (UN, 1985).

In Israel, it is estimated that an average increase in rainfall of 18 to 19% over five seasons was achieved by cloud seeding. The gain in precipitation due to seeding generally occurred as the result of large increases in a few days of seeding, whilst on most days of seeding only minor or no increases were recorded. At an estimated increase of 15% in precipitation (significance level of 1.2%) at a cost of seeding of \$600 000 (1981), the additional rainfall resulting from cloud seeding was equivalent to 39 million m^3 per year, and the estimated increase in GNP due to increased rainfall was \$11.5 million per year (Kloner, 1981).

Rain cannot fall from a dry atmosphere, and therefore even the most successful rain making can, at best, only contribute to an increase in rainfall, but cannot consistently provide rain to arid regions.

Economic aspects of water use

In many regions, the development of agriculture is dependent on irrigation; in others it is a prerequisite to higher productivity of limited land resources, to production of high-value crops, and to the diversification and intensification of agriculture.

As a result, irrigation development has a considerable impact on overall economic development: increased employment and generally increased living standards provide an internal market for industrial products; moreover, raw materials such as textiles, sugar, vegetable oils, etc., are produced for industrial processing.

Frequently, the development of water resources is undertaken by governments even when the cost of the water that is eventually made available to agriculture is more than the producer can afford to pay; water is therefore frequently subsidized in one form or another. The vital role of water in food production and as an essential starting point for overall economic development justifies, in these cases, the development of water resources as a national asset, while indirect benefits are sometimes sufficient to pay for the maintenance, operation, and interest charges, of the project.

Alternate uses of water

In most arid and semi-arid regions of the world, competitive demands for a finite supply of water are increasing. Competing with agriculture for water are industry, municipal requirements, environmental and recreational needs (including tourism). In arable areas, the largest of these demands is for agriculture, which often uses 80% of the total water supply.

The amount of drinking water needed each year by human beings and domestic animals is of the order of 10 tonnes per tonne of living tissue. Industrial water requirements for washing, cooling, and the circulation of materials range from one to two tonnes of product in the manufacture of bricks to 250 tonnes per tonne of paper and 600 tonnes per tonne of nitrate fertilizer. Even the largest of these quantities is small compared with the amounts of water needed in agriculture. To grow a tonne of sugar or maize under irrigation, about 1000 tonnes of water are 'consumed'. Wheat, rice, and cotton fibre use about 1500, 4000, and 10 000 tonnes of water per tonne of crop, respectively (Revelle, 1966).

Unlike the situation in humid areas, where land has its own intrinsic value, in arid regions land is almost valueless without water; its value is determined by the amount of water available to the land (Koenig, 1956).

An economic evaluation of alternate uses of water shows that agriculture is far less productive in its use of water than are other users (Ackerman, 1960). The productivity value of water for industry is frequently 100 times as great as for agriculture (Olivier, 1967). In the San Juan basin in Colorado and New Mexico, it was estimated that the productivity of an acre-foot ($= 1233.5 \text{ m}^3$) of water in irrigation was \$14 to \$18 – as compared with \$1200 to \$3300 when it was used for industrial or municipal purposes (Wollman et al., 1959, as cited by G.F. White, 1962). In a survey by the United Nations of developing countries in dry regions, it was found that – in addition to industry – mining, ports, tourist centres, and all other economic activities, could afford to pay far higher costs for water than could agriculture (UN, 1964). In the

United States, the water that will support one worker in arid-land agriculture will support about 60 workers in industry (Koenig, 1956).

However, factors other than the economic return per unit of water have to be considered – such as the need to provide for a minimum local production of food, the displacement of the agricultural population, and even, in certain cases, security needs which may be overriding. All these considerations, which are certainly legitimate, have to be weighed against the economic evaluation of alternate uses of water.

As capital is one of the scarcest resources in a developing economy, errors in the economic evaluation of irrigation projects can have far-reaching consequences in retarding economic development.

In the long run, economic considerations will be overriding in the determination of priorities for the use of water, which is a basic resource for which demand increases far more rapidly than does supply.

Most development programmes in Third World Countries have focused on the expansion of water supply to the agricultural sector. However, with increasing urbanization and industrialization, the share of water by agriculture in overall water use is bound to decline in the developing countries. For example, in Mexico, total water supply is projected to increase by 137% between 1980 and 2000, but the share of agriculture is expected to decline by about 20 to 30% during this 20-year period (FAO, 1985). Pollution of water by industrial and urban wastes is bound to increase, making more water unfit for agricultural use.

As the relative contribution of agriculture to the national economy declines, painful policy decisions have to be made on a reallocation of water resources from agriculture to relatively higher value uses leading to feasible economic restructuring and a sustainable water economy (Sexton, 1990).

Naturally, a politically powerful agricultural sector will oppose curtailment of its water supplies in order “to keep expensively developed irrigated land in production” (Sexton, 1990). This opposition is counterproductive, as the future prosperity of the agricultural sector is founded on the overall development of the national economy, such as a shift to industrial growth, and not on the interests of a narrow sector. If capital is deployed where water end-use economic efficiency is low, this involves an inefficient capital allocation and becomes “a drag on the rest of the economy” (Sexton, 1990).

From a review of the situation in Israel and Jordan, two formerly predominantly agrarian economies in which the process of industrialization and non-agricultural development has become preponderant, Sexton (1990) concludes that a reduction in water allocations to agriculture will result in a cut-back on the least valuable use of water and will involve crops which in most cases are already economically marginal.

Value, cost and price

The price of water is what the user pays for it; it may be less than cost if the price is

subsidized. Value may range from zero, for a farmer paying a flat rate per unit of area farmed, to infinity, for a wanderer dying of thirst in the desert. A country will generally first develop its lowest-cost water resources, which are usually in proximity to the areas to be irrigated. As needs increase, more distant water sources have to be drawn on; water is pumped from greater depths, and more and more expensive water resources are developed.

At present, the price paid for irrigation water by the farmer in most countries is usually below total costs. In many cases, he does not even pay on the basis of the actual amount of water used, but according to the area irrigated or the crop grown. There is little doubt that this approach is conducive to the waste of water, to inefficiency in its use, and to the production of crops that are not economically justified. If the objective is to subsidize agriculture, more appropriate means can be adopted.

Yaron (1966) proposes a system whereby a relatively low price is fixed for the bulk of the farmer's water allocation, and a far higher price, in the range of the value of the marginal output of water on efficient farms, for the remainder. The result of such a policy would be that only efficient farms would purchase and use the full quantity of water allocated to them, and that therefore even the marginal segment of the water supply would be efficiently used.

Marginal costs of water

In countries with a high level of agricultural production, linear programming makes it possible to calculate the amounts of water that are economical to apply, at various price levels for water.

The cost limit of the marginal value product of water can rise, as a result of improved technology involving more efficient use of water, reduced production costs, higher yields, or the growing of higher-value crops.

Where water is the limiting factor, it is usually preferable to aim for the highest yield per unit of water applied than per unit of land area. The total production from the water may be much higher when the supply is spread over a fairly large area in amounts calculated to give less than maximum yields than when it is concentrated over an area on which it will produce maximum yields. In Tunisia, it was found that 80% of the maximum possible yield of maize was obtained with 60% of the water needed for potential evapotranspiration (Perrin de Brichambaut and Wallen, 1963).

Such 'under-irrigation' is, however, possible only in those areas in which, during at least part of the year, precipitation is sufficient to leach the salts beyond the root zone.

Cost of water from different sources

Costs of water for irrigation are naturally dependent on the source of supply, being generally lowest when it is drawn by gravity from flowing streams or springs, higher when it is pumped from wells, and generally highest with water from reservoirs created by constructing dams.

The advantage of developing groundwater supplies is in the relatively low capital requirement. It is interesting to note that the raising of water from wells by primitive methods, by man and animal power, is barely remunerative – even at a relatively high value for grain and a very low cost of labour (Clark, 1967).

In most of the developing countries, low-cost water resources are already fully exploited and further development requires heavier investment and higher unit costs.

Desalinated water

The key to the use of desalinated water is, of course, substantial reduction in the costs of conversion. Although considerable progress has been achieved, the final goal – i.e., a cost of conversion compatible with using the desalinated water for irrigation – has not yet been achieved.

The major costs involved in desalination are: capital investment, the cost of the energy used for the process, and operation and maintenance costs. To the cost of desalination must be added the expense of conveying the converted water to where it will be used. As the source of supply is always at sea level, costs of lifting may be quite considerable.

When considering the cost of desalinated water, its effect on the quality of the overall water supply should also be considered. By blending it with waters which would otherwise be too saline for use, supplies of water available to irrigation can be considerably increased.

Conversion of brackish water by electrodialysis may already be competitive in areas where the water supply is limited and water costs are marginal.

Water legislation

Historically, in certain countries, water was considered as a free commodity, like air, which could be used by anyone having the need and the opportunity to do so. The rational development of water cannot, however, be achieved without appropriate legislation, that defines the rights and duties of the water users.

In those countries in which water legislation already exists, the growth of the population, technological progress, and additional uses for water, frequently make the existing laws obsolete. New legislation is then essential if progress in water development and use is not to be hamstrung.

Cano (1967) lists the following desiderata for national water laws: water legislation should define the national water policy principles covering standards for planning, definition of priorities, government authorization for private works, and also measures for integration of water resources for multiple use. Water laws must also cover relations among individuals and between individuals and government. Proceedings for registration and protection of rights and uses must be established in order to ensure security and stability of investments. Legal rules are required on technical

methods to ensure conservation and prevent waste, as well as on those relating to prospecting, extraction, and use of underground water.

Two examples of the basic principles of water legislation are given below: one is in force in the United States, a country in which the water law is no longer in accordance with present-day requirements, while the other is in force in Israel, a developing country with scarce water resources on which development is entirely dependent.

Water legislation in the United States

In the United States, water legislation in the humid regions is derived from English law and based on riparian doctrine which accords water rights only to owners of land that is adjacent to a stream (Riesbol et al., 1967). All riparian owners are entitled to fair shares of the water, which could be used only for riparian lands. Whether or not the owner uses his prerogatives, has no effect on his rights.

The arid-regions doctrine, called 'appropriation doctrine', was based on the customs of miners who diverted waters for their operations, as well as on the experience of the early Spanish settlers who conveyed water from the streams to their lands for use in irrigation. According to this doctrine, the first to appropriate the water has priority of rights, which are subject to his actually using the water; lack of use usually results in loss of rights. The water can be used for riparian lands, or at a distance from the streambed, at the discretion of the appropriator. The great advantages of the appropriation doctrine, are the requirements of beneficial use and the discretion to convey the water to where it is most needed. Its main disadvantage is that a farmer with a right to much water would tend to be wasteful of this resource.

Groundwater is usually subject to the English rule that gives to the owner of the land absolute control of the underlying groundwater. However, this law entirely neglects the basic fact that water under a certain piece of land belongs to a common underground reservoir, and that surface water and underground water cannot be treated separately (US Geological Survey, 1951). After the development of efficient pumping systems, and their extensive use, the shortcomings of the common law in this respect have become increasingly evident.

The absolute right of the owner of a well to pump, without any restrictions, generally leads to over-use of groundwater resources. As a result cones of depression have developed in wells in many areas (Thomas, 1955). Natural recharge often being very small, stored water continues to be depleted.

Water legislation in Israel

In Israel, *all* water resources of the country – surface and underground waters, floodwaters, wastewaters and drainage waters – are public property and are controlled by the State (Aloni, 1967). No water can be owned by a private individual, even if it is found on his own land; nor does this confer on him any preferential rights.

As agriculture uses about 80% of the total supply, the implementation of the water law is the responsibility of the Minister of Agriculture, under whom a Water Commissioner manages all the water affairs of the country.

One of the main provisions of the law is that water rights, allocated to an individual, are linked to a specified purpose. If the purpose ceases to exist, or is not adhered to, the water right lapses. Water allocated to a farmer, e.g., can be used for growing any crop he wishes, but if he ceases to farm his land, his water rights lapse, and cannot be transferred to another location.

The Minister of Agriculture can prescribe norms and rules for the efficient and economic use of water in all parts of the country.

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PART II

Crops under Moisture Stress

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CHAPTER 5

Crop – Water Relations

There are few subjects of significance to agriculture that have been subjected to such an intensive research effort as that of plant–water relationships. In a review of progress in this field of study, Turner (1986) states that during the decade 1976–86, there have been nearly 15 000 articles published on plant–water relations, i.e., an average of four papers every day!

The availability of soil moisture, its uptake by the plant, its translocation through the plant, and its evaporation into the atmosphere are various steps in the movement of water through the soil–plant–atmosphere system. Hence plants, in their relationship with water, are influenced by the interactions of the components of the system, and not by the individual values of each component viewed separately (Lemon et al., 1957).

Properties of water and its role in plants

Properties

Water has a unique combination of characteristics which make it biologically of outstanding importance (Kramer, 1969). Its specific heat, latent heat of melting, and heat of vaporization, are very high. The phase change from liquid to vapour requires more than six times as much energy as the exchange from vapour to liquid (Fitter and Hay, 1987).

These characteristics have important implications for the thermal economy of plants. The high specific heat of water buffers the plant against rapid changes in air temperature, whilst the high latent heat of evaporation is an effective means of cooling leaves by transpiration (Gates, 1976).

Water has a high density, high surface tension, and considerable tensile strength. It is adsorbed by surfaces, such as clay and cellulose, which have many oxygen atoms with which hydrogen bonds can be formed. Water is also an excellent solvent for electrolytes and numerous other substances.

Role

The characteristics of water described above are reflected in the many and varied functions fulfilled by water in plant life.

A field crop assimilates about 1–2% of the water it takes up in the course of its active life; the rest is lost by transpiration. The small proportion that is retained is essential to the life and growth of the plants, in many ways.

The functions of water in the plant are summarized by Sutcliffe (1968):

- It is the main constituent of the protoplasm, and makes up 85–95% of the fresh weight of most of its tissues.
- Much of the water in plants is found in large vacuoles within the protoplasts, where it has the mechanical function of maintaining plant turgor, on which depend normal growth, and the maintenance of the form of various plant organs and their mechanical strength.
- Many, if not all, of the physiological and biophysical processes related to photosynthesis depend on cell turgor potential.
- It participates directly in many chemical reactions in the protoplasm.
- It is involved in photosynthesis as the source of H atoms for the reduction of CO₂, and it is a product of respiration.
- Water forms a continuous network of films in the microspace within and between the solid material in the cell wall (the apparent free space) throughout the plant; these films are involved in the entry and movement of dissolved substances.
- It participates in many chemical reactions in the protoplasm.
- Water is the medium in which solutes and suspended substances move in the vascular vessels, and through which motile gametes or nuclei effect fertilization.
- It plays an important role in the dissemination of spores, fruits and seeds.

Water potential

The concept

Since the 1960's the concept of *water potential*, based on the thermodynamic principle that water, "in pursuit of thermodynamic equilibrium, will obey the universal tendency to move from where the potential energy is higher to where it is lower" (Thien, 1983), has been widely advocated and used in the literature, to define water movement in the soil–plant–atmosphere continuum.

The great advantage of this concept is that it encompasses the potential energy of water in each of the three components of the soil–plant–atmosphere continuum, as well as in the system as a whole, and that it provides a unified terminology for studies in soil–plant–atmosphere relationships (Mengel and Kirkby, 1982).

Water movement in the soil–plant–atmosphere system is activated in response to certain forces, so it possesses potential energy (i.e., ability to do work) in the three components of the system. Water may be subjected to hydrostatic pressure (which increases water potential) or to suction (which has the opposite effect).

In a transpiring plant that is well supplied with water, the free-energy status of the water declines gradually as it passes through the soil to the roots, through the xylem to the transpiring leaves and into the atmosphere. For water to move against a gradient from a high energy potential to a point of low energy potential a force in the contrary direction has to be applied, i.e., work has to be done. The potential energy of water (called for convenience water potential) is defined relative to pure water at a specified temperature and elevation.

Force fields acting on water

The force fields acting on the soil water are matrix, solute, pressure, and gravitational forces. The total soil water potential is the algebraic sum of these potential components:

$$\psi = \psi_m + \psi_s + \psi_p + \psi_z$$

The *matrix potential* (ψ_m) is due to suction forces resulting from surface tension effects in soil and plant capillaries, and adsorption of water to the cell walls and membranes. These forces restrict the mobility of water, and the sign of ψ_m is therefore negative.

Solute (or osmotic) potential (ψ_s): the addition of solutes to water reduces water potential, as compared to pure water under the same conditions; therefore ψ_s will have a negative value.

The *pressure potential* (ψ_p) is the result of hydrostatic pressure acting on soil water; an increase in pressure increases the water potential; ψ_p therefore has a positive sign.

The *gravitational potential* (ψ_z) is, as its name implies, the result of differences in water level, depending on its location in different parts of the soil–plant system; its values can be positive or negative, according to the location in relation to the reference point. In tall trees, the gravitational potential may be significant; for field crops the force required to overcome gravity is so small that it can be ignored.

Water potential can be expressed as energy per unit mass or unit volume. It is generally expressed per unit volume, which can be reduced to units of pressure such as bars, atmospheres or dynes per cm². The most recent to be used are pascals (Pa, kPa and MPa).

Water in the soil

The soil as a water reservoir

Water is held in the soil mainly by matrix forces which bind the water on the soil particles, and to a lesser extent, by osmotic forces due to the presence of salts in the soil solution. However, in soils of the dry regions, and in irrigated soils in particular, the osmotic potential may become an important component of total soil water potential.

Infiltration

The rate of infiltration of water from rain or irrigation is of considerable importance: low infiltration rates increase run-off with resultant loss of water and soil erosion.

The main factors influencing the rate of infiltration of water into the soil are: initial water content, surface permeability, compaction, soil porosity, degree of swelling of soil colloids, organic matter content, duration and intensity of rainfall, and temperature of soil and water (Musgrave, 1955) (Fig. 5.1).

Sandy soils have a large proportion of macropores, and therefore rapid infiltration rates. As the proportion of silt increases, average pore size decreases, and infiltration is slowed down.

Increasing the clay content of the soil can have two opposite effects on infiltration: the clay increases aggregate stability, thereby enabling a high initial rate of infiltration; the considerable number of micropores and the puddling of the soil surface result in a very slow final infiltration rate (Thien, 1983).

Redistribution and equilibrium

After water enters a soil, it is subject to attractive forces and to gravity. At first it moves downwards, fairly rapidly filling all pore spaces and saturating the soil to a depth which depends on the amount of water applied and on specific soil characteristics.

Expressed in its most simple form, redistribution of water and the resultant equilibrium generally occur as follows:

After one to three days, the films covering the soil particles become so thin that moisture movement becomes negligible, representing a water potential of -0.3 bar or less (Kramer, 1969). Drainage practically ceases; the moisture content at this stage is called field capacity (FC).

At FC, there is a 'wetting front', a region of very steep gradient which is the visible limit between the wetted part of the soil and the dry soil underneath (Kramer, 1969). It must be stressed that the above applies only to a *well-drained soil*. When an impermeable layer is present near the soil surface, or the groundwater table is high, the root zone may remain waterlogged for long periods. Another factor affecting the precision of the field-capacity concept is extraction of water by the growing crop, during the

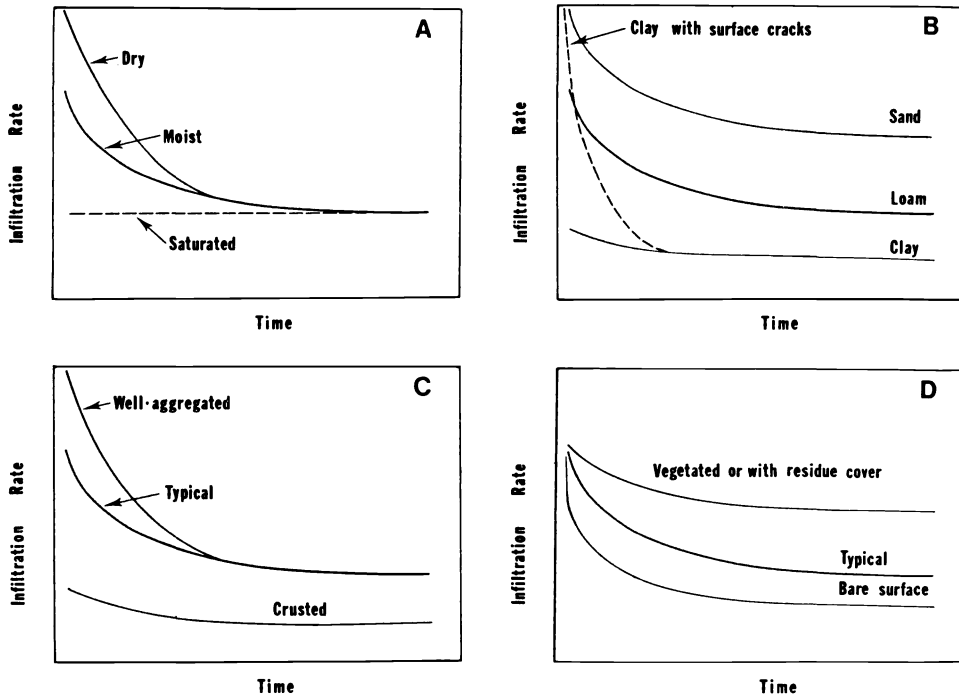


Fig. 5.1. Soil conditions and infiltration rates. (a) When water is partially or completely filling the surface pores further infiltration is reduced. (b) Large pores in sandy soils allow faster infiltration than the small pores of finer-textured soils. Surface cracks facilitate infiltration until swelling causes their closure. (c) A well-aggregated soil presents large, open surface pores, while a crusted soil, resulting from structure breakdown, seals the surface pores and inhibits infiltration. (d) A mulch of crop residues delays or prevents crusting, by insulating the soil surface from raindrop impact. From Thien, 1982. Reprinted by permission of John Wiley & Sons, Inc. Copyright © 1982.

period of time between the application of water and the attainment of field capacity in the soil. This affects the rate of downward flow and losses beyond the root zone, and cannot be considered as a negligible influence within reasonable times after irrigation (Miller, 1967).

In the soil's wettest condition, the soil water potential (SWP) is zero and it increases to $-10\,000$ bar after drying at temperatures over 100°C . Under natural conditions, the SWP will seldom fall below the hygroscopic coefficient of air-dry soil (-31 bar).

For crop production, -10 to -20 bar (with an average -15 bar) is generally the practical limit, at which plants wilt and eventually die if water supply is not renewed (Thien, 1983). The exact values depend on the kind of plant and the conditions under which wilting occurs (Kramer, 1969).

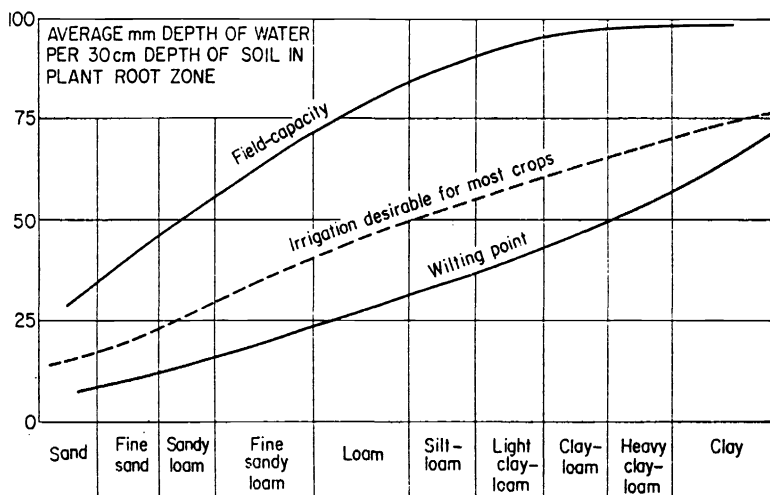


Fig. 5.2. Typical water-holding characteristics of different textural soils. By courtesy of the US Department of Agriculture, Washington, DC.

Water-binding forces

Water is held in the soil in the same way as in a porous matrix. The pores between the soil particles, and between their aggregates, are linked by narrow passages having some similarity to capillary tubes. The water fills the interstices between the soil particles and is held as a film on the soil particle surfaces.

The force with which water is held in the soil depends on its water content; the drier the soil, the more tightly the water is held, and the more work is required to extract water from the soil (Hadas, 1973).

Water will be removed from a saturated soil by gravity, which empties the water from the largest pores and crevices. Water then moves in films surrounding the soil particles, and water movement is mainly controlled by the matrix potential. Suction is needed to remove water from smaller pores. As suction forces increase, progressively finer capillaries and smaller pores release their water, and finally, at about -15 bar, only films of water on colloidal particles remain (Thien, 1983). At this stage, the continuity of the liquid films is broken and water moves only in the form of vapour (Kramer, 1969).

The major soil properties related to forces binding water are (a) texture and colloidal content, and (b) porosity.

Soil texture (Fig. 5.2)

The principal property of soil particles affecting the water-binding forces of the soil is their surface area. On these surfaces, important soil reactions take place, including the attraction and binding of water.

The specific surface area of clay particles is tremendous because of their small size and, in the case of clay minerals, because of their plate-like shape and layered structure which contribute to the active interior surfaces (Thien, 1983).

The water layers directly adjacent to the adsorbing surfaces of soil particles may be bound by forces as high as -6000 bar (Mengel and Kirkby, 1982).

Soil porosity

The porosity of the soil depends primarily on its texture, but can be modified by compaction or, conversely, by improving the soil structure. Porosity values range from 35% or less of void space/soil volume for the most severely compacted soils, to 65% for well-aggregated soils high in colloid and/or organic matter content (Thien, 1983).

Micropores (<0.01 mm) are the most useful for water storage, medium-sized pores ($0.01-0.06$ mm) facilitate capillary conductivity, and macropores (>0.06 mm) allow rapid infiltration and drainage, and improve aeration (Thien, 1983).

The intensity with which water is held in the capillary soil pores depends on the diameter of the pores. As the diameter of the pores decreases the water binding becomes stronger. Pores with a diameter in excess of 0.05 mm are too large to retain water after the soil has been brought to field capacity. In addition to the adsorption forces which bind water molecules to the walls of soil pores, the water molecules are attracted to each other by cohesive forces; the combined effect of the adsorption and cohesive forces enables water to rise in the soil by the capillary force. The height of the capillary rise increases as the size of the soil capillaries becomes smaller. This capillary rise can be important for the water supply of plants from deeper soil layers (Mengel and Kirkby, 1982).

Water-holding capacity of the soil

The *field capacity* is defined as the amount of water in a soil after the force of gravity has removed all the water not held by the matrix potential (-0.33 bar). Soil conditions make it difficult to predict exactly when the field capacity is reached.

Available water

The availability of water to a crop depends on a combination of soil and crop factors. The two major soil factors involved – (a) total water content of the soil and its distribution within the soil profile, and (b) the extent to which the water is bound to the soil particles – have been discussed in the previous section.

Crop plants are generally able to extract water from the soil until a soil water potential of about -15 bar is reached; at this stage the water potential gradient necessary for inducing the flow of water across the soil–plant–air continuum disappears and the leaves of a standard test plant will wilt and fail to regain turgidity in a saturated atmosphere. This moisture content is called the *wilting point* (WP).

It should be stressed that the values for FC and WP mentioned above are not

sharply defined, but “merely represent approximate values on the water-potential/water-content curve” (Kramer, 1969).

The amount of water held in the soil between the field capacity and the wilting point has long been considered as representing the reservoir of water available for plant use. The capacity of this reservoir depends on the depth of the soil, its texture and its structure. For each crop, in turn, it will depend on the depth and extent of the root system. The latter depends not only on the genetic characteristics of the crop, but also on the presence of hardpans, poor drainage, nutrient deficiencies, toxic substances, etc. These aspects will be discussed in more detail in the section treating water uptake by crop plants.

A distinction has been made between the wilting point – which is the water potential at which a plant ceases to grow, but from which it can recover if water supply is renewed – and the *ultimate wilting point* at which the plant can no longer maintain life. The difference between the two is called the *wilting range* (Furr and Reeve, 1945). The ultimate wilting point is a dynamic value determined by specific plant and soil properties (Thien, 1983).

The rate of water movement through the soil, called *hydraulic conductivity*, is controlled mainly by the gravitational potential in soils above FC, and by the matrix potential in soils drier than the FC.

Hydraulic conductivity is important in determining how near to the WP plants can withdraw water without suffering setbacks in growth.

As the soil water potential decreases, hydraulic conductivity decreases very rapidly, so that movement in a dry soil is very slow and practically ceases at a water potential of -15 bar (Kramer, 1969).

Different soils have different hydraulic conductivities, so that different rates of flow can be related to the same bulk water potential in different soils. In a sandy soil, the moisture content can be reduced to near WP without markedly affecting water flow, and consequently plant growth, whilst the effects of soil moisture tension on plant growth will make themselves felt at moisture levels above WP in a heavy soil (Fig. 5.2).

Soils with a hydraulic conductivity of less than 0.25 cm/h are poorly drained, whilst those with conductivities greater than 25 cm/h do not hold enough water for satisfactory plant growth (Kramer, 1969).

In general, values of available water for differently textured soils are (in mm m^{-1}) (Bunting and Kassam, 1988):

fine-textured soils: 200
medium-textured soils: 140
coarse-textured soils: 60

It should be stressed that there is no sharp limit between ‘available’ and ‘unavailable’ water, and that the WP is “only a convenient point in a curve of decreasing water potential and decreasing availability” (Kramer, 1969). Despite this limitation, ‘avail-

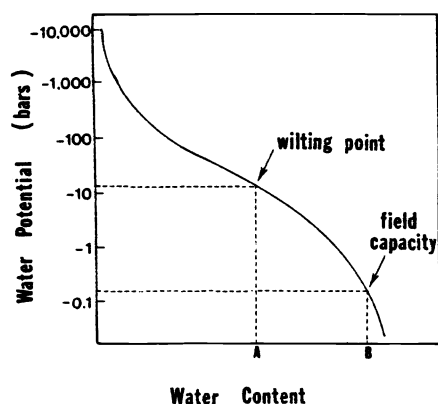


Fig. 5.3. Representative soil moisture retention curve illustrating the relationship between soil water potential and soil water content. The water between points A and B represents available water content. The exact shape of the curve depends on specific soil properties. From Thien (1983). Reprinted by permission of John Wiley & Sons, Inc. Copyright © 1983.

able water' remains a useful concept for crop management, and, in particular, irrigation practice.

A graph of the complete relationship between soil water potential and water content is called a *soil water retention curve*, a schematic presentation of which is given in Fig. 5.3 (Thien, 1983). The curve shows that the removal of successive increments of water always requires logarithmically higher amounts of energy. This explains why all water in a soil is not equally available to plants, and why plants wilt even when there is still water in the soil.

Water in the soil–plant–atmosphere continuum

Water uptake and transfer system

Water transfer through the soil–plant–atmosphere continuum takes place in response to a water potential gradient. The hydraulic system within plants acts as a true continuum, as evidenced by the fact that pressure changes in the roots are evident in the leaves (Blad, 1983).

Water movement through the soil–plant–atmosphere system involves three phases: water uptake by the plant, water movement through the plant, and water loss to the atmosphere. Though the system should be considered as a continuum, it is necessary, in order to present a clear picture, to describe its individual components, and the resistances encountered in each one, by water on its path from the soil to the leaves.

Plant properties that determine water uptake are the water potential that can be achieved by the roots, the structure of the root system, the ability of the root system

to extend, and the anatomical characteristics of the roots with respect to water absorption.

Xylem vessels and a network of capillaries in the cell walls enable water movement through the plant, and the stomata serve as a regulatory system for water loss to the atmosphere.

Plant water potential

Formerly, *water content* was the measure generally adopted to define the water status of the plant; this criterion was subsequently replaced by *relative water content* (RWC), in which the water content was expressed on the basis of the fully rehydrated tissue.

The possibility of measuring total water potential of plant organs by thermocouple psychrometry and the pressure chamber technique, (cf. Ch. 12) led to the widespread adoption of *total water potential* as the measure of plant water status. For reasons of convenience it is the water potential of the leaf that has become the primary index of crop water status (Turner, 1986).

Water uptake

Water uptake by the roots can only occur when the root water potential is lower than that of the soil. Roots absorb water both passively and actively.

Passive absorption takes place when water is drawn into the roots by negative pressures in the conducting tissues, resulting from transpiration. As evaporation takes place from the leaves, there is a general lowering in the water potential of the leaves, and the resultant potential gradient is the driving force of passive absorption of water from the soil. Water then moves from the soil surrounding the roots, along the water potential gradient through the plant, and so into the atmosphere.

Active absorption: under conditions during which there is little transpiration loss and yet ample moisture is available to the plants, the roots of many plants are known to absorb water actively (Slatyer, 1960). The water is then exuded into the stem under pressure (called *root pressure*). In seedlings root pressure can cause guttation: the exclusion of droplets which is often observed in the early morning partly as the result of the low water deficit of the atmosphere which restricts evaporation. Guttation results from intense root metabolism and high root pressure (Mengel and Kirkby, 1982).

In active absorption by slowly transpiring plants, the reduction in water potential of the xylem sap is mainly due to the accumulation of solutes in the sap, and pressure on the sap is positive. In passive absorption by rapidly transpiring plants, the removal of water from the xylem reduces pressure in the xylem sap and reduces its water potential. This reduction is transmitted right down to the root system. The

pressure in the xylem sap is often below atmospheric pressure, so that water is pulled in through the roots, which act as passive absorbing surfaces (Kramer, 1969).

Under conditions of normal high transpiration, the contribution of active absorption to the water supply of the crop is negligible, as compared with passive absorption, and is usually less than 10% of the total water absorption by the plant (Kramer et al., 1967).

Factors affecting water uptake

Uptake of water by crop plants is controlled by two groups of factors: (a) factors that influence the difference in water potential from soil to roots, and (b) those which affect the resistance to water flow in the soil to the roots (Kramer, 1969).

Soil texture and hydraulic conductivity influence water uptake mainly through their effects on resistance to water movement through the soil to the roots. These have been discussed in a previous section.

Crop factors. Rooting characteristics. The water potential at the soil/root interface is generally considered to be the major soil value controlling the availability of water to plants (Slatyer, 1960).

Both root proliferation and depth of penetration are important characteristics. Roots may have an enormous surface area in intimate contact with soil particles.

Water moves in the soil toward a single root along a gradient of decreasing water potential. If water is to enter the root, the latter must be in contact with the soil and have a lower water potential within the root. As the root withdraws water from the soil, it has to readjust its water potential in order to maintain water uptake. If the uptake rate equals the rate at which water is supplied by the soil, the root's soil water flow system is said to be at a steady state (Hadas, 1973).

An active root system extends new roots most of the time; since water uptake is fastest near the tips of new roots, the rates of water uptake may be different at various depths and locations within the root zone.

The wilting point is not reached at the same time throughout the root zone. When plant roots remove water from the soil, moisture in the immediate vicinity of the roots may be depleted to the wilting point very rapidly. The high soil-moisture tension that develops in the soil enveloping the roots creates a potential gradient, as a result of which there is a tendency for water to move towards the roots. This movement is, however, extremely slow, and limited to a few centimetres. The slow rate of movement of the soil water towards the roots may frequently cause a lag in water uptake in relation to transpiration demands, and as a result plants may wilt temporarily – especially during the hot hours of the day.

In order to maintain a satisfactory rate of water intake that will be sufficient for sustained growth, the roots, especially those of young plants, must grow actively towards the moist regions. The soil may be at field capacity at a distance of a few centimetres from a zone that has been depleted to the wilting point by the roots. As

the root system becomes more and more extensive and completely permeates the root zone, the soil moisture content is reduced to the wilting point throughout progressively expanding root zones.

Crop species and varieties. The level of depletion that a crop can tolerate without affecting its growth and/or actual evapotranspiration (ET_a) varies with type of crop and even with varieties of the same crop.

Crop plants, whose root systems develop rapidly, will be able to explore a greater volume of soil for moisture and will therefore be at an advantage over crops whose root systems grow slowly. Deep penetration of their roots provides many crops with a continued supply of soil moisture, even when the upper layers, which usually dry out between rains or irrigations, have already reached WP.

The quantity of water that is *readily available* to a crop is defined as $p(S_a)$, where p is the fraction of the total available water that can be used by the crop without affecting ET_a and/or growth, and S_a is the total amount of available water stored in the soil.

The value of the empirical fraction p depends in part on the type of crop, the soil and the evaporative demand (Bunting and Kassam, 1988).

There are considerable differences in depth and density of rooting between crops and varieties of the same crop. These root characteristics also change in the course of plant development.

Even after the soil is too dry for root growth to be maintained at its maximum rate, root growth of certain crops can continue. For example, root growth of maize and tomatoes can occur at -40 bar total soil water potential and root tips can remain alive even at much lower potentials (Portas and Taylor, 1976); wheat plants with a well developed root system were found capable of absorbing water at tensions greater than -26 bar (Haise et al., 1955).

Some crops, usually with shallow and sparse root systems, such as strawberry, potato and onion, cannot tolerate a marked reduction in the total available moisture supply; other crops, such as cotton, wheat, and safflower will continue to grow with less readily available moisture. However, the level of depletion that can be tolerated varies greatly according to the stages of development; many crops are most sensitive to limitations in water supply during heading and flowering, and up to fruit and seed setting.

The fraction p also varies with the level of evaporative demand. When ET is small, the crop can tolerate the depletion of a greater proportion of available soil water (S_a) than when ET is large. The difference will be greater in fine-textured soils than in coarse soils.

Additional factors that influence p are root characteristics (discussed in a previous section), leaf and tissue water relations, and crop development characteristics (Bunting and Kassam, 1988).

On the practical level, the question of the lower limit of extractable water is important for the calculation of water uptake by crops, and hence for estimating the length

of the growing season and for predicting the onset of significant stress. A reasonable approximation of this limit is 30% of the total available water in the root zone, at which point the ratio of actual to potential transpiration would be 0.6–0.7 (cf. Ch. 12).

An alternative proposed by Sinclair and Ludlow (1986) is to define the lower limit of available water in terms of the decrease of the transpiration rate, which is reached when the stomata have closed and transpiration has become negligible. This definition has direct physiological relevance to crop production, because any water used after closure of the stomata does not contribute to photosynthesis; soil water that is extracted during a protracted survival phase is also not included.

Using this concept of transpirable soil water, the authors suggest that plants pass through three distinct physiological phases as soil water is progressively depleted from the upper to the lower limit of availability:

Phase I. Stomata are open and transpiration is determined primarily by meteorological conditions. No inhibition of photosynthesis due to water stress occurs.

Phase II. For most crops, this phase begins when the fraction of transpirable water remaining in the soil becomes 0.2–0.3; water demand exceeds water supply, and stomatal conductance is reduced to maintain a balance between the two. With the partial closure of the stomata, the rate of photosynthesis is reduced.

Phase III. This phase begins when all transpirable water is exhausted and no further reduction in stomatal conductance is possible; the crop is in a survival mode and the relative plant water content decreases slowly.

Aerial absorption of water. A further possibility raised by Slatyer (1958) is that moisture may be absorbed by plants even from an unsaturated atmosphere, as long as there is a favourable diffusion-pressure deficit gradient. This is of special significance in semi-arid and arid zones, where high air humidity levels and dew fall are frequent at night.

Direct absorption of water by leaves that are wetted by rain, dew, or overhead irrigation, can help resaturate dehydrated tissues; but proof of a real contribution to the amounts of water absorbed by plants, causing greater growth or productivity, is lacking. The main contribution of the wetting of leaves is apparently by reducing transpiration somewhat, thereby reducing the water deficit and prolonging survival (Slatyer, 1967).

Environmental factors. Soil temperature. The temperature of the soil can have a marked effect on the rate of water uptake by the roots; low soil temperatures reduce the absorption rate of water; this is probably due to the increased viscosity of water, which impedes its movement through the soil, and through the roots into the plants (Curtis and Clark, 1950). The permeability of cells to water also decreases, as a rule, at lower soil temperatures. These effects are compounded by the reduced growth of

roots at low temperatures; not only is absorption then more difficult, but the absorbing root surface is also decreased (Kozlowski, 1964).

Plants differ in their sensitivity to soil temperatures. Water absorption is more reduced at low temperatures in warm-weather crops such as cotton or maize, than in typical cool-season crops, such as the small grains. The temperature below which water absorption by warm-weather crops becomes limiting is approximately 20°C (Kramer et al., 1967).

In the middle-latitude dry regions, considerable killing of crop plants may result from desiccation caused by transpiration at a time when the soil is so cold that water absorption is slowed down and cannot replace water lost by transpiration. By contrast, in the low-latitude regions, the temperatures are sometimes high enough in agricultural soils to be a limiting factor in water uptake (Kramer, 1969).

Solute potential. In arid regions, salt accumulation in the root zone, in various degrees, is the rule. Even a small increase in electrolytic concentration in the soil solution may cause relatively large decreases in water uptake (Kozlowski, 1964). In addition to its effect on water availability, a solute potential lower than -2 to -3 bar also has undesirable indirect effects on plants by reducing root growth and the permeability of roots to water. Soils with osmotic potentials approaching -40 bar are generally barren of vegetation (Kramer, 1969).

Soil aeration. Inadequate aeration of the soil decreases absorption of water; many factors influence the severity of the damage caused to the plants: the species, temperature, soil flooding and its duration, type of soil, etc. (Kramer, 1969).

Atmospheric factors. All factors affecting transpiration (cf. p. 196) indirectly affect water uptake, as they affect the plant's need for water and consequently the demands it makes on water supply. We will return to this subject in a later section.

Water movement through the plant (Fig. 5.4)

Root pressure and capillary forces alone are too weak to play a major role in the upward transport of water through the xylem.

A continuous water phase extends from the soil solution through the entire plant. As the leaves become dehydrated by transpiration, a chain reaction occurs: the turgor of the leaf cells, and consequently cell volume, are reduced and the water potential in the leaves decreases. The resultant energy gradient causes water to be absorbed from the water-conducting tissues. The reduction of pressure on the water extends right through the conducting system, to the roots and into the soil.

Capillary action and the cohesive properties of water ensure that water moves into the roots and continues to flow through the plant to replace the water lost by transpiration. This concept of water movement is known as the *cohesion hypothesis* (Mengel and Kirkby, 1982).

Water movement through the plant is facilitated by the presence of specialized

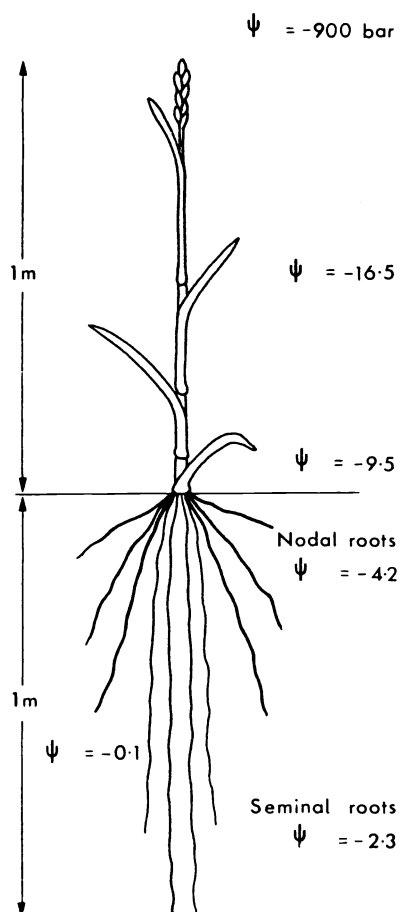


Fig. 5.4. Water potentials expected at different points of the pathway for water transport through a wheat plant. Growing in soil at a potential of -0.1 bar and in an atmosphere with a potential of -900 bar. From Turner and Burch (1983). Reprinted by permission of John Wiley & Sons, Inc. Copyright © 1983.

elongated cells (tracheids) or rows of cells with the ends broken down and forming a more or less continuous system of 'vessels'. Tracheids and/or vessels constitute the main functional components of the xylem, through which water can flow with a minimum of resistance, from the roots, through the stem, and into the leaves. This is the situation in all normal vascular and other 'higher' plants, including the seed plants or Spermatophyta to which virtually all crop plants belong.

The two processes of transpiration and water absorption are closely correlated, the transpiration by the leaves producing the tension which causes passive water absorption. However, because of the resistance to the movement of water through the roots, the xylem, and the leaf, absorption tends to lag behind transpiration (Kramer, 1959).

Such lags in absorption, due to the internal resistance to water transport within plants, are common even at high levels of soil moisture. The lag is aggravated as soil moisture-tension increases or soil temperature is reduced, or when environmental conditions favour a high rate of transpiration.

In order for the water to ascend to the top of the plant, it must have sufficient cohesion to withstand the tension needed to pull it upwards. When water is confined to small, completely wettable tubes, such as the xylem elements, it can be subjected to a pull of many atmospheres and still maintain its cohesion (Dixon, 1924).

Plant-atmosphere interface

The driving force which enables the translocation of water from the soil solution, through the plant to the atmosphere, results from the fact that the water potential of the atmosphere is usually lower than that of the soil. It is at the interface leaf-atmosphere that there is a large difference in potential; it is also at this interface that resistance to flow is the greatest. This resistance varies with wind speed, leaf shape, and leaf surface morphology.

Crop plants expose a considerable leaf surface area to the atmosphere, so as to capture the energy and CO₂ required for photosynthesis. This, however, entails a considerable loss of water by transpiration.

Between the leaf cells are numerous interconnected air spaces which lead to the atmosphere through small openings in the leaf – the stomata. When the water vapour pressure of the atmosphere in contact with the leaf is lower than that within the air spaces within the leaf, water diffuses from the leaf into the surrounding air; the rate of this transpiration is proportional to the difference in water vapour pressure between the two media.

Most of the water that is lost to the atmosphere by transpiration escapes through the stomata; however, under conditions of water stress, when the stomata are closed, transpiration through the cuticle may become an important factor in water loss (Milthorpe, 1960).

The stomata respond to light, humidity, CO₂ concentration, temperature, and leaf turgor. Under similar environmental factors, stomatal response differs among species, and the most extreme differences are due to different photosynthetic pathways – from very low resistances in C₃ plants, to complete closure of the stomata during daylight of CAM plants.

Transpiration

Role

There are two schools of thought regarding the role of transpiration. The one considers transpiration as a necessary evil, the other as an unavoidable evil (Curtis, 1926).

It is an evil, because frequently absorption of water lags behind transpiration,

causing water deficits in the plant tissues – with adverse effects on photosynthesis and growth, with disruption of metabolic processes, and in extreme cases, with resultant death of the plants.

It is a necessary evil: “transpiration is the dominant factor in plant–water relations, because evaporation of water produces the energy gradient which causes water movement into and through plants. Therefore it controls the rate of absorption and the ascent of sap” (Kramer, 1959).

Transpiration is considered an unavoidable evil because it is inevitably linked to photosynthesis. CO_2 diffuses into the plant, and at the same time water vapour diffuses out of the plant into the atmosphere, only as long as the stomata are open. The loss of water by transpiration is therefore inevitable as long as the plant is assimilating CO_2 .

Plants which have very low rates of transpiration also have very low rates of photosynthesis and grow slowly (Hygen, 1953). Maximum rates of photosynthesis and growth are related to maximum rates of transpiration (Penman, 1952).

Heat dissipation

The foliage of a crop intercepts a quantity of radiation that is far in excess of its ability to use effectively. Leaves subjected to a heavy radiation load must be able to dissipate the excess energy quickly, or their temperature would rise to lethal levels within less than a minute (Idso et al., 1966).

This dissipation of heat is possible through three mechanisms: thermal radiation of the leaf, removal of heat by convection currents, and transpiration.

For most cultivated crops, the transpiration of large quantities of water is considered by many authors to be the main mechanism for this purpose, each gram of water removing the energy equivalent of 580 cal (Thorntwaite and Mather, 1954). Because of the high heat of vaporization, leaves of actively transpiring plants are usually 2–3°C cooler than leaves with closed stomata (Turner and Burch, 1983).

Another school of thought states that the role of transpiration in cooling plants has little practical significance. The temperature of wilted leaves was found to increase by only 2–5°C, when transpiration was slowed down. According to Ansari and Loomis (1959), the main factor in preventing an excessive rise in leaf temperature is the removal of heat by air movement.

When transpiration is reduced, convective cooling increases; only under conditions of high radiation incidence and very low wind velocity, would there be a danger of excessive leaf temperature as a result of reduced transpiration (Gale and Hagan, 1966). Moreover, in hot, dry regions, the stomata of plants close during the hottest hours of the day, when the cooling effect of transpiration would be most needed. However, as pointed out by Gates (1964), when the leaf temperature approaches a lethal level, transpiration, by reducing the leaf temperature even by a few degrees, may swing the difference between survival and death.

Nutrient supply

Transpiration fulfils another useful function; the movement of water into the plant, as a result of transpiration losses, helps bring dissolved nutrients to the root surface, and carries them into and through the roots and the vascular system to the rest of the plant.

Transpiration rate (Bunting and Kassam, 1988)

The amount of water transpired per day by a plant or crop (the transpiration rate) is influenced by: (a) the evaporative demand of the air and the number of hours that the stomata remain open; (b) the size of the leaf area that is intercepting radiant energy, reflected and advected heat; and (c) the water supply.

If the transpiration rate is greater than the rate of water uptake, a water deficit develops and the leaf water potential decreases; water potential gradients are thereby set up in the plant. These gradients cause water to be ‘sucked’ from the soil into the plant. When the transpiration rate decreases at night or on humid days, and provided water is available in the soil, rehydration takes place until an equilibrium is reached between water potentials of leaves and soil.

The steepness of the gradients, at a given evaporative demand, depends on crop, variety, growth stage and water supply. When water is freely available, the water potentials of field crops tend towards zero overnight. During the daytime, water deficits generally develop. Typical leaf water potentials are generally greater than -0.5 MPa when water is freely available. As water shortage develops, the water potential becomes more negative, and at some point, there is partial or complete closure of the stomata in response to changes in the turgor potentials of the guard cells.

If the plant water deficits continue to increase, then the number of hours during which the stomata remain open decreases, leaf temperature rises, and osmoregulation occurs. Initially, the decrease in osmotic potential maintains a positive cell turgor potential as water potential continues to decrease, but later serves to avoid irreversible dehydration.

Environmental factors affecting transpiration rate

Evaporative demand of the air (Bunting and Kassam, 1988). The evaporative demand of the air is determined by: (a) the net amount of radiant energy received by the leaves of the crop, which provides the latent heat of evaporation; (b) the temperature and relative humidity of the air; and (c) the movement of the air, which carries water vapour away from the leaves, and may also bring less humid air from hotter and drier locations.

The evaporative demand of the air can be calculated using a procedure developed by Penman (1952) (cf. Ch. 12).

The desiccating effect of the atmosphere is the main factor influencing the water needs of the plant. The plant is a water-conducting system between the soil and the

atmosphere. The overall free-energy difference of the water moving into, through, and out of, the plants is from 0.1 to 15 atm in the soil, and about 1000 atm in the atmosphere, when the relative humidity of the air is 47% (Richards and Wadleigh, 1952).

The sensitivity of plants to increasing soil moisture stress increases under conditions of high temperature, low relative humidity, high wind velocity, and increased light intensities – all conditions which increase the transpiration rate considerably.

Therefore, on a hot dry day, the rate of transpiration is so much in excess of water uptake that plants will wilt at a soil moisture content at which on a cooler or more humid day they would not have shown any signs of stress.

Other environmental factors. Visible light, which has no direct effect on evaporation, affects the rate of transpiration by influencing the stomatal aperture. Cloudy weather, especially during the cool season, causes decreased stomatal opening in most species that are native to sunny habitats (Wilson, 1948). The availability of soil moisture also modifies transpiration, with water deficits causing a rapid decrease in transpiration.

Crop cover. In the early growth stages of an annual crop, before the ground is fully covered by the crop canopy (especially in the case of widely spaced rows) part of the radiant energy falls on bare soil and is re-radiated from the soil surface. As the crop canopy approaches full cover of the soil surface, the rate of water loss increases to a maximum, at which point it may be equal to the evaporative demand of the air.

Actual evapotranspiration varies during crop development; the actual evapotranspiration rate is generally a fraction of PET. Transpiration is equal to PET multiplied by a crop coefficient. An example of this relationship for maize is given in Fig. 5.5, in which the crop coefficient ranges from a value of about 0.2 early in the season, to values near 1.0 during part of the vegetative and reproductive stages (Cassel, 1984).

Methods for decreasing transpiration

Antitranspirants

As more than 90% of the water taken up by the plant is lost by transpiration from the leaves, researchers have long proposed the use of antitranspirants to reduce loss of water under moisture stress conditions.

Photosynthesis is inevitably linked to loss of water by transpiration, since the stomata serve both processes. However, partial closure of the stomata has a greater effect on water loss than on CO₂ uptake (Raschke, 1976). Since the diffusion pathway for water and the gradient driving water out of the leaf is steeper than that driving CO₂ inwards, the amount of water transpired is greater than the amount of CO₂ fixed (Fitter and Hay, 1987).

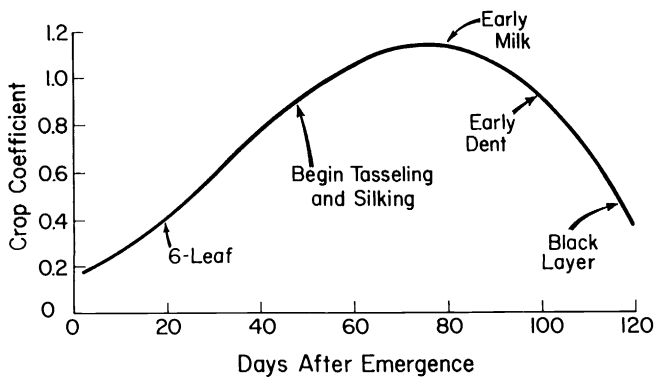


Fig. 5.5. Variation in crop coefficient in the course of development of maize. From Cassel (1984). By permission of American Society of Agronomy.

There are three basic types of antitranspirants: compounds that cause stomatal closure, film-type compounds, and reflectants (Das and Raghavendra, 1979).

Compounds that cause stomatal closure

Spray materials used for various purposes, such as certain herbicides, fungicides, metabolic inhibitors, and growth hormones, have been found to cause the closing of the guard cells of the stomata and thereby reduce transpiration (Gale and Hagan, 1966). However, their concurrent effects on other plant processes were in most cases not recorded. Phenylmercuric acetate (PMA), a fungicide, was found to decrease transpiration to a greater degree than photosynthesis, in a number of plants (Zelitch and Waggoner, 1962). The main drawback of PMA is the relatively short period during which it remains effective (Gale and Hagan, 1966).

Film-type compounds

Plastic and waxy materials that cover the stomata with a film which has a greater resistance to the passage of water than to that of CO_2 and O_2 , are being sought. The characteristics required, in addition to selective gas-permeability, are easy application, inexpensiveness, and non-phytotoxicity – also the ability to form a continuous film on the leaf surface, to resist degradation, and to retain elasticity (Gale and Hagan, 1966).

However, all film materials tested have a greater permeability to water than to CO_2 , and therefore seriously reduce photosynthesis (Jones, 1983).

Film-type antitranspirants also present difficulties in application and maintenance. Full coverage of leaves might require 40–50 kg/ha. There is also the problem of

maintaining the film coatings in spite of dew and light rains and of removing it when moisture supply is again favourable (Loomis, 1983).

Presently, these compounds are mainly used for reducing post-harvest shrinkage of fruits, and preventing wilting of transplants.

Reflectants

Reflectants can reduce the amounts of solar radiation absorbed by the leaves. An ideal reflectant would transmit light in the photosynthetic bands and reflect light in other wavelengths.

Most reflectants however, have a broad reflectance over the whole short-wave spectrum, and therefore cause a decrease in photosynthesis together with decreasing transpiration (Loomis, 1983). Thus, in soybeans treated with kaolinite, reflectance in the photosynthetic range increased up to 300%, and there was little effect on reflectance at other wavelengths (Das and Raghavendra, 1979).

Problems of coverage and maintenance are similar to those encountered with film coatings.

In brief. Although new materials may be developed that are more satisfactory as antitranspirants, those that are currently available are too expensive and/or have a negative effect on dry-matter production to be useful for field crop production (Das and Raghavendra, 1979).

Increased CO₂ concentration in the air

If a practical and economical method of increasing the normal carbon dioxide concentration in the air were developed, it would be possible to cause the closure of stomata as a result of increased CO₂ concentration, concurrently with increased photosynthesis, provided sunlight was not limiting. When the CO₂ concentration over maize plants was increased from 0.0310 to 0.0575%, transpiration was reduced by 23% and net photosynthesis increased by 30% (Moss et al., 1961).

Growth retardants

Certain growth retardants have been found to reduce the plant's susceptibility to water stress, but this may be imputed to a lower top : root ratio and not to reduced transpiration (Plaut et al., 1964).

Weed control

Since time immemorial controlling weeds has been known to be one of the most effective means of increasing the amount of water available to the crop. Weeds frequently transpire greater amounts of water per unit of dry matter produced than do the crop plants with which they grow in association.

Planting patterns

One of the adaptations to limited rainfall in arid climates is the use of wide spacings between the rows of crop plants, so that, during a relatively long period of plant growth, more soil is exposed to radiant energy than is the case in humid climates. As a result, the rate of evaporation from the soil is greater. If precipitation occurs in the form of relatively frequent and light rains, the wide spacing may result in loss by evaporation of a very large proportion of the total precipitation.

Physiological effects of water stress

Water stress affects almost every aspect of plant growth and development and influences the anatomy, morphology, physiology and biochemistry of crop plants (Kramer, 1969). Some of these effects will be described in this section.

Water deficits occur in the plant whenever transpiration exceeds water absorption: this may be due to excessive water losses, to reduced absorption, or to both.

According to the degree of internal water deficit and its duration, one can distinguish between incipient, transient, and permanent wilting (Kramer, 1959). A small loss in turgor, causing incipient wilting, is an almost daily occurrence in warm, dry weather, even when the soil is moist. This does not produce visible symptoms of wilting. A more severe loss of turgor, causing leaf drooping and subsequently spreading through the plant, will reduce growth. If plants regain their turgidity when the water supply is rebalanced, this is termed 'temporary wilting'. A longer period of dehydration causes 'permanent wilting', from which plants are no longer able to recover – even in a saturated atmosphere.

A transient water deficit is a frequent occurrence experienced by plants in dry regions and, in the course of evolution, plants have developed a number of mechanisms to cope with such deficits at various stages in their development. These are discussed in detail in Ch. 6.

Unavoidably, despite these adaptive properties, water deficits generally have adverse effects on the plants, some of which may be irreversible.

Stages in plant growth

A growing crop may be subjected to a water deficit continuously throughout the entire growing period, or at specific stages in its development, such as at emergence, vegetative growth, flowering, yield formation or ripening.

For many crop plants, the critical period is the time pollination and fertilization occur, and reproductive organs are formed (Kramer, 1969).

Reasons for a differential response at different stages of development include (Hay, 1978):

- the very large leaf areas of plants at the end of vegetative development;
- the diversion of photosynthates from roots to developing fruit at the beginning of flowering;
- in gramineae, the severe, but temporary, disruption of the vascular system of the stem during rapid internode elongation.

Effect of water stress on photosynthesis

When plants are subjected to water stress, net photosynthesis is often observed to be at first relatively unaffected by the leaf water potential; as stress increases, photosynthesis decreases markedly, often reaching zero at greater stress levels (Pearcy, 1983).

Water stress can affect photosynthesis directly, by affecting various biochemical processes involved in photosynthesis, and indirectly, by reducing the intake of CO₂ through the stomata of the leaves, as a result of their closure in response to water stress. Soil water stress and atmospheric water deficit act additively in reducing the rate of photosynthesis (Baker and Musgrave, 1964).

An adverse water régime also reduces leaf area and hastens leaf senescence, thereby decreasing the productivity of the crop to a greater extent than the depressive effect resulting from a reduced net assimilation rate (Fisher and Hagan, 1965). For example, water stress that reduced the net assimilation rate by only 50% was sufficient to cause complete cessation of leaf growth, indicating that leaf area is more affected by water stress than is the case for net assimilation rate (Ashton, 1956).

Respiration

Respiration generally responds to loss of turgor in the inverse direction of photosynthesis: the respiration rate first increases, but, as the deficit becomes more severe, it decreases (Evenari, 1962).

Anatomical changes

Periodical water stress leads to many anatomical changes: these include decreases in the sizes of cells and of intercellular spaces, thicker cell-walls, and greater development of the mechanical tissues (May and Milthorpe, 1962). However, the number of stomata per unit of leaf surface tends to increase (ibid.).

Metabolic reactions

The proportion of water in the plant is far higher than in the soil, and very small fluctuations, within very narrow limits, can interfere with active metabolism (Slatyer, 1967).

Almost all metabolic reactions are affected by plant water deficits. Hydrolytic reactions increase: starch is hydrolyzed into sugars, and proteins into amino-acids. It has been found in cotton that, as a result of water stress, the sugar content of the leaf increases and starch content decreases. By contrast, in the stems, the concentration of both sugar and starch increases – indicating that the reduced water supply not only affects photosynthesis, but also that the ability of the plant to utilize the products of photosynthesis is still more impaired (Eaton and Ergle, 1952). Similar results were obtained with wheat, in which the percentage of soluble carbohydrates in the leaves of plants under moisture stress increased steadily, reaching a level from three to four times as high as that in irrigated plants – after which death followed (Petinov, 1961).

The conversion of starch to sugars, and their accumulation, increases osmotic pressure. This causes a reduction in the permeability of the plant cell, so that internal resistance to water flow increases, thereby lessening water loss (Shields, 1958).

Water deficits impair the nucleic acid system as a result of increased R-nase activity; the degradation of RNA proceeds more rapidly than its synthesis, and this, in turn, affects enzyme production and growth (May and Milthorpe, 1962). Protein synthesis is intimately connected with the activities of the nucleic acid system, and is therefore also affected by drought (Kessler, 1961).

Hormonal balance

A number of hormones have been observed to change when a plant is subjected to water stress, but most research activity has concentrated on abscisic acid as the stress hormone (Turner, 1986).

The abscisic acid content of leaves remains unchanged until a threshold leaf water potential is reached, and then rises markedly with little further change in water potential. The water potential at which abscisic acid accumulation accelerated corresponded to zero turgor pressure (Pierce and Raschke, 1980).

The increase in abscisic acid (ABA) levels following water stress occurs irrespective of whether the changes in water potential are due to soil drought, high evaporative demand, or salinity. Cytokinin (CK) treatment has the opposite effect on ABA levels than that due to water deficits (Itai and Benzioni, 1976).

High and low abscisic acid lines of wheat, which differ in stomatal conductance have been developed, but the differences were not large; morphological differences between the lines, such as smaller leaves, fewer tillers and spikelets and a greater number of ears per plant, were probably the cause of the differences in water use efficiency (WUE) and yields observed (Innes et al., 1984).

Hsiao (1973) has suggested that water stress primarily causes turgor reduction which retards growth; this in turn causes metabolite accumulation which then results in all water stress responses, including changes in hormone levels. Itai and Benzioni (1976) consider hormonal balance as the primary effect and the other responses as secondary ones. This hypothesis suggests that “plants evolved to cope with water

stress by an inbuilt ‘flow-sheet’ regulated by the hormonal balance CK/ABA”. These authors base their argument on the fact that stress factors such as heat, salinity, mineral deficiencies, and boron toxicity cause hormonal changes and other stress symptoms similar to those caused by water deficits, without changes in plant turgor.

Root development

Root development is affected by soil water potential in a number of ways, among which we should note the following:

- The growth rate of roots decreases with increasing water stress; however, growth of the roots is less affected by water shortage than is that of the aerial parts, so that the overall shoot : root ratio is increased (Peters and Runkles, 1967).
- When only a small fraction of the potential root zone is wetted, as happens when irrigations are light and frequent, root penetration will be restricted and the crop will be particularly sensitive to drought periods at a later stage.

Growth

Water deficits cause a dehydration of the protoplasm, associated with a loss of turgor. The expansion of cells and cell division are reduced, resulting in a decrease in the growth of stems, leaves and fruits. The final effect on growth will depend on the frequency and the duration of the periods of water stress. It is therefore necessary to determine, for each crop, at what stages of development it can tolerate soil moisture stress, so that an irrigation schedule can be planned that will produce the maximum economic yield per unit of water or per unit of area – whichever is most limiting.

Water stress does not affect all organs of the plant equally; as a rule, there is a decrease in the ratio of leaves to stem. Older leaves and those that are shaded are usually the first to die under water stress (Peters and Runkles, 1967).

Reproduction and grain development

Moisture stress during the vegetative phase may stimulate the reproductive phase in some plants (Richards and Wadleigh, 1952). Aerial or storage parts of the plant may be adversely affected by a certain low level of soil moisture, whilst the economic yield may remain unaffected. For example, cotton was found to show marked differences in growth at different levels of moisture supply that had no significant effect on the yield of cottonseed (Adams et al., 1942).

For many crop plants, moisture stress at the flowering period is critical. Even a short period of water stress at anthesis will markedly reduce the number of flowers that set seed (May and Milthorpe, 1962). The critical period in cereals begins with the appearance of pollen mother-cells (pollen viability appears to be particularly susceptible) and ends after pollination (Henckel, 1964). This is especially marked in crops

with determinate flowering, in which the period of pollination through seed set is relatively short. Grain yields of maize were found to be reduced by 25% when soil moisture was depleted to WP for two days during the tasselling period, and by 50% when the period of stress was increased from six to eight days (Robins and Domingo, 1953). Water stress during maturation of the grain will usually result in small or shrivelled grains.

Bierhuizen (1976) postulates that the increased sensitivity of many crop plants to drought stress during the change from vegetative to reproductive growth, may be due to a lag in root growth: senescence of root growth from the vegetative to the regenerative phase decreases water uptake at a time of higher evapotranspiration.

Crop yield

The effect of water stress on yield will depend largely on what proportion of the total dry matter produced is considered as useful material to be harvested (Fisher and Hagan, 1965).

When the yield consists of most or all of the aerial part of the crop (forage crops, tobacco, etc.), the effects of stress on yield are much the same as those on total growth.

When the yield consists of storage organs other than seeds or fruits (stock beets, potatoes, etc.), it will generally be as sensitive to moisture stress as is the plant's total growth.

When the yield consists of the seeds or fruits, the situation is very different, and it has been shown for a number of crops that the dry matter stored in the seeds or grain is mainly the result of photosynthesis that occurred after flowering (Thorne, 1966). The effect of water stress will therefore depend on the stage of growth at which it occurs. At an early stage, the number of primordia formed may be reduced; on the other hand, the drastic effect of stress at the time of flowering has already been indicated above. In general, water stress, except at the most critical time, will have less effect on the yield of grain than on the plant's total growth.

For certain plants, such as lucerne, moderate water stress during flowering may improve seed set, and hence yield. This is ascribed to the increased sweetness of the nectar, which attracts a greater number of pollinating insects.

When the yield is a chemical constituent (sugar, pharmaceuticals, fibres, etc.), the economically valuable part of the crop is only a small fraction of the total dry matter produced, and moderate stress that affects growth may have no, or even a beneficial, effect on yield. For example, the content of essential oils in *Mentha* decreases sharply shortly after irrigation (Lvov, 1954), the assumption being that wilting favours the decomposition of starch and proteins, which stimulate the formation of the essential oils. Other examples cited by Kramer (1969) are an increase in the aromatic properties of Turkish tobacco, the rubber content of guayule, the alkaloid content of *Datura*, *Atropa belladonna*, and *Hyoscyamus muticus*.

Yield response factor

Doorenbos and Kassam (1979) calculated the response of yield to water supply by relating relative yield decrease to relative ET deficit, expressed as 'yield response factor' (k_y). A few examples illustrate the differences in response to moisture stress between plants and between different crop growth periods (Table 5.1).

Sequential effects of water deficits on plants

Slatyer (1967) has described the sequence of effects on plants of water deficits as they become progressively more severe.

A plant that has an adequate water and nutrient supply, and normal transpiration, will have accelerated breakdown of RNA (without any cessation of RNA synthesis). Metabolism will, at first, be impaired only during the daily periods of maximum water deficit; but these periods will become progressively longer. Stomatal closure during these periods will lead to reduced transpiration and also CO_2 absorption; photosynthesis is reduced and leaf temperatures are increased. Increased respiration will further reduce apparent photosynthesis.

As cell turgor decreases, the rate of cell enlargement is reduced, causing a slow-down in the expansion of leaf area, resulting in reduced growth rates.

As the moisture stress in the soil approaches the PWP (permanent wilting point), turgor pressure in the plants approaches zero. Cell enlargement virtually ceases, and the rate of cell division is markedly reduced. The stomata remain closed for most of

TABLE 5.1

Yield response factor (k_y)

Crop	Vegetative period	Flowering	Yield formation	Ripening	Total
Lucerne	0.7–1.1				0.7–1.1
Bean	0.2	1.1	0.75	0.2	1.15
Cotton	0.2	0.5		0.25	0.85
Groundnut	0.2	0.8	0.6	0.2	0.7
Maize	0.4	1.5	0.5	0.2	1.25
Pea	0.2	0.9	0.7	0.2	1.15
Potato	0.45		0.7	0.2	1.1
Sorghum	0.2	0.55	0.45	0.2	0.9
Wheat					
winter	0.2	0.6	0.5		1.0
spring	0.2	0.65	0.55		1.15

Based on Doorenbosch and Kassam (1979). By permission of the FAO.

the day, and transpiration is limited to cuticular transpiration. Leaf temperature will increase markedly. Most metabolic processes, including respiration, slow down, apparent photosynthesis and production of dry matter becoming practically nil.

The disruption of normal cell metabolism is accompanied by the breakdown of proteins and carbohydrates, causing an increase in the concentration of sugars; leaf phosphorus and nitrogen migrate from the older leaves to the stems.

Finally, as protoplasmic dehydration continues, individual cells and tissues die. Root hairs die and the roots suberize. In some cases the tops of plants die before the roots, in others the opposite occurs.

Effects of renewed moisture supply after stress periods

Whilst cases of crop desiccation and hence complete loss are not rare in arid and even semi-arid regions, what generally happens is that the crops suffer periods of stress of varying in duration and severity, terminated each time by a renewed supply of moisture. This is true even under irrigation – either because the farmer does not have full control over timing of his water supply, or because he does not have the full quantities of water required. Competing demands of other crops for water at the same time, the need to economize in the use of water, exceptional atmospheric conditions, mechanical breakdowns in water supply, the normal cycle of wetting and drying between irrigations – all these and other factors ensure that practically every crop, even under irrigation*, experiences periods of stress. It is consequently important to understand crop reactions to a renewed water supply after periods of stress of various degrees of severity and duration, and at different stages of growth.

Recovery of photosynthetic efficiency occurs rapidly on reduction of moisture stress (Baker and Musgrave, 1964). The initial decrease in the rate of photosynthesis as a result of water deficit may even be followed by an increase to a point exceeding the original level (Eckardt, 1953). This phenomenon is not well understood (Evenari, 1962). Rapid drying has a more adverse effect on the rate of photosynthesis than does slow drying (Stocker, 1960).

The ability of stomata to recover after moisture stress may be impaired, so that the plant is unable to re-establish its normal functions even after regaining turgescence. There are, apparently, differences between various crops in the ability of their stomata to recover from the effects of water stress, and this may be a factor in their apparent drought resistance. Presumably, this is one of the reasons for the greater ability of sorghum to recover from the effects of drought as compared with maize (Glover, 1959).

If the moisture supply is renewed only shortly before death would have occurred, metabolic processes do not immediately return to normal (Denmead and Shaw,

* With the possible exception of drip irrigation.

1960). The death of the root hairs and the suberization of the roots delay recovery – because of the reduced capacity for water uptake by the stressed plant, the complete dislocation of the metabolism of the plant, and the senescence of the previously active leaves (Slatyer, 1967).

Recovery from the adverse effects of water stress may depend on the stage of growth at which the stress occurred. At certain stages, there may be irreversible damage which will affect final yield; at other stages, a renewed water supply may stimulate growth to such an extent that the plant may ‘catch up’.

Effect of moisture supply on crop quality

Carbohydrates

Carbohydrates are the cheapest and most abundant source of calories for human nutrition: they include sugars, starches, and, to a lesser degree, cellulose.

Below certain moisture levels, the rate of photosynthesis is progressively reduced (Eaton and Ergle, 1948), both as a result of the dehydration of protoplasm which affects its photosynthetic ability, and because the closure of stomata reduces the supply of CO₂ (Ståfelt, 1956). During periods of drought there may also be losses of carbohydrates, owing to increased respiration (Aslying, 1956). The combination of decreased photosynthesis and increased respiration implies a potential decrease in carbohydrate reserves in the plant, which may be partially compensated for by the reduction in vegetative growth and the concomitant decrease in utilization of carbohydrates in growth (Richards and Wadleigh, 1952). By reducing the amounts of food available for various biochemical processes in the plant, important changes in its chemical composition may be brought about. Under conditions of water stress, the hydrolysis of starch is accelerated through increased amylolytic activity (Woodhams and Kozlowski, 1954) and sugar concentration is increased, resulting in increased osmotic pressure (Mothes, 1956). As a consequence, plants that have been submitted to water deficits usually show a decrease in their proportion of starch to total sugars, and, in most instances, a decrease in total carbohydrate reserves (Richards and Wadleigh, 1952). These effects may be noted even in cases when moisture tension is not sufficiently severe to cause wilting (Woodhams and Kozlowski, 1954).

The effects of moisture stress on sugars are less consistent than those on starch. Richards and Wadleigh (1952) state that this is undoubtedly related to the transitional nature of sugars in various plant tissues. Whilst Clements (1943) showed that sugar levels in cane are negatively correlated with growth and moisture supply, Hartt (1934) presented evidence that more sucrose is synthesized in leaves of sugar cane that is well supplied with water than in plants under moisture stress. Woolley and Bennett (1962) showed that the percentage of sucrose in sugar beets responds in a linear manner to increasing soil moisture.

Moisture supply affects sugar accumulation in plants in different ways:

- (1) An adequate moisture supply is essential for efficient photosynthetic activity and hence for sugar synthesis.
- (2) Favourable moisture régimes increase growth and hence increase the utilization and depletion of sugars.
- (3) Moisture stress causes a direct loss of water from the tissues and increases hydrolysis of starch, resulting in an increased concentration of sugars.

It follows that, under both moist and dry régimes, there are conflicting effects of moisture supply on sugar accumulation in plants.

Arnon (1962), working with 22 varieties of sweet sorghum, showed that the sugar concentration in this plant is a result of soil-moisture-variety interactions. Varieties that are generally low in sugar content show an increase in sugar concentration under conditions of moisture stress, whilst in varieties with a potentially high sugar content, the sugar concentration is adversely affected by moisture stress.

Janes (1948), working on snap beans, also reported a variety-moisture-régime interaction in relation to sugar content. There was a significant difference in total sugar content expressed as percent of dry weight: the beans from the light irrigation plots had the lowest sugar content in the variety with an inherently low sugar content, whereas no difference was observed between plots in the variety with an inherently higher sugar content.

Proteins

Although favourable soil moisture conditions increase nitrification and thereby increase the amounts of nitrogen available to plants, irrigation may carry readily soluble nitrogen beyond the root zone. This would explain the contradictory results found in some cases, e.g. with tomatoes, in which nitrogen uptake was reduced by irrigation (Cannel et al., 1962), and with lucerne, clover, and grasses, in which it was increased (Kilmer et al., 1960).

Increasing moisture tension in itself does not appear to limit the ability of plants to extract nitrate from the soil, as long as moisture is above the wilting point. Whilst uptake of nitrate can be maintained under conditions of moisture stress, the reduced growth as well as the decrease in available phosphorus reduce nitrate utilization. This explains why the concentration of nitrogen in plants almost consistently increases with a reduced water supply (Bourget and Carson, 1962; Bennett, 1964). This holds true on both a fresh and a dry-weight basis. The stage of growth at which moisture stress occurs may affect this process (Kramer and Russell, 1959).

There is consistent evidence that moisture stress during maturation increases the protein content of grain. Yields of grain may be adversely affected, but most studies show that there is an inverse relationship between moisture availability during maturation and high protein content of wheat (Dubetz, 1961; Sosulki et al., 1963) and maize (Greaves and Nelson, 1925).

Water use efficiency

Definitions and concepts

Water use efficiency (WUE) can be related to two very different aspects: *hydrological* and *physiological* (Stanhill, 1986).

In the hydrological context, WUE relates primarily to the efficiency with which water is used in irrigation, and is defined by Bos and Nugteren (1974) as “the increase in water content of the root zone following irrigation, expressed as a fraction of the total water supplied to the irrigated area”. The hydrological aspect of WUE is treated in Ch. 12.

In the context of crop–water relations, we are concerned with the physiological concept of WUE, and its agronomic implications, i.e., the yield of dry matter as a function of the total water used to produce a crop. Because it is difficult to determine the weight of roots (typically, 0.10–0.20 of the total crop mass at maturity (Gregory, 1988)) only the above-ground biomass is considered.

Formerly, many authors used the term *transpiration ratio*, which is usually in terms of total dry weight of the above-soil biomass (or of the fresh weight of the yield component) in relation to transpiration or, alternatively, of total water loss, e.g., evapotranspiration. In some studies, the transpiration ratio is mentioned as transpiration/photosynthesis.

In recent years, some authors have questioned the appropriateness of the terms water use as well as water use efficiency, and the older term, transpiration ratio, has made a comeback (Stanhill, 1986).

In the present context, the term water use efficiency (WUE) will be used in its most widely accepted form, namely the ratio yield/water-use (Y/ET), the latter term refers to water lost by transpiration and evaporation.

For most crops only part of the dry matter produced is of economic significance to the farmer (e.g., grain crops), therefore the economic proportion of the total dry matter (Y_{ec}) can be substituted in the relationship, and we have the agronomic definition of water use efficiency:

$$WUE = Y_{ec}/ET. \quad (1)$$

In this form, the equation relates to the beneficial utilization of water for producing a crop and therefore reflects our main preoccupation. Gregory (1988) proposes an expansion of eq. (1),

$$WUE = \frac{Y_{ec}/T}{1+(E/T)}, \quad (2)$$

where Y_{ec}/T is the transpiration efficiency. In semi-arid conditions in which run-off (R), drainage (D), and interception of rainfall by crop canopies (I) are substantial components of the water balance, Gregory suggests:

$$\text{WUE} = \frac{Y_{\text{ec}}/T}{1+[(E+R+D+I)/T]}. \quad (3)$$

Equations (2) and (3) are useful because they indicate how it is possible to improve WUE:

- by increasing the numerator – transpiration efficiency (Y_{ec}/T);
- by increasing T proportionally more than the other water losses.

Overall, the transpiration efficiency is a function of plant physiology, whereas the components of $E+R+D$ are amenable to soil and crop management.

The practical conclusion to be drawn from the above is that every effort should be made to increase the amounts of water available to the crop for production, and to reduce to a minimum the water losses due to evaporation, run-off and drainage.

At first sight, these two objectives may appear to be at cross purposes – but actually the contradiction is more apparent than real. Fortunately the effects on yields of an increase in T will almost always be proportionally greater than the increase in $(E+R+D)$, so that WUE is generally improved by an improved water supply, even though the latter signifies an increase in the denominator of the equation.

The numerator: yield

Harvested yield will reflect the composite effects of all the factors that have influenced the crop during its lifetime. The difference between harvested yield and potential yield for the available water supply represents the amount of yield improvement that could be achieved by maximizing the efficient use of water.

Yield and WUE can be increased by (Barnes, 1983):

- improving soil and water management practices: fertilization, seedbed preparation, conservation tillage, water harvesting, etc.;
- improving crop management: timely plant establishment, pest, disease and weed control, timely harvesting, etc.;
- growing high-yielding, stress-tolerant and widely adapted cultivars. These should have economic levels of disease, insect, and nematode resistance, tolerance to stress (water, heat, salinity, cold, toxicity, etc.), relative insensitivity to normal temperature and photoperiod fluctuations.

The denominator: evapotranspiration

Because it is difficult to measure E and T separately, most data simply combine the two. For the sake of convenience, two factors are being coupled, one of which (transpiration) has a positive effect on yield and hence on WUE, and the other (evaporation), has, on the contrary, a negative effect on WUE. It would therefore be desirable to estimate these two components separately, in order to assess the potential benefits of manipulating each component (Ludlow and Muchow, 1990).

Transpiration. The T component has already been discussed in detail (cf. p. 196).

Good and Bell (1980) explain why the amount of water lost from widely different crops is essentially similar when these crops are subjected to the same isolation:

Most of the water loss through transpiration is used for essential evaporative cooling. While the stomata play a major role in controlling water loss, it is unlikely that they have much control over the amount of water lost by the canopy as a whole. Rather, water use depends mainly on absorbed radiation, which is not under the plant's control; therefore, once the leaf area index (LAI) reaches or exceeds three in conditions of ample water supply, water use approaches PET and any crop uses the same amount of water (Reitz, 1974), and WUE is mainly determined by the rate of CO_2 uptake by the crop.

Many workers have established that biomass accumulation is linearly related to cumulative transpiration. This means that in order to achieve high yields, the fraction of available water that goes to transpiration should be maximized (Ludlow and Muchow, 1990) (Fig. 5.6)..

The quantities of water available to the crop can be increased by:

- increasing water storage in the root zone, by improving infiltration, by water harvesting, and by irrigation;
- reducing to a minimum the losses of water due to evaporation, run-off, drainage, by management practices such as conservation tillage, fallow, mulching; weed control, planting patterns and density.

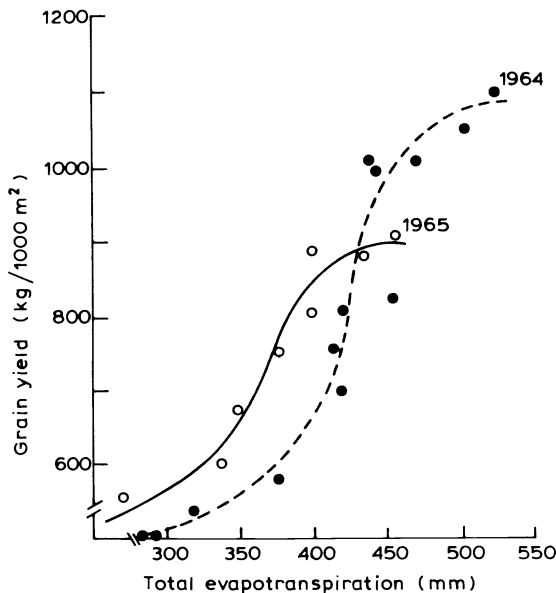


Fig. 5.6. An example of the close relationship between grain yield and total evapotranspiration (sorghum, during two seasons). From Plaut et al. (1964). By permission of the American Society of Agronomy, Inc.

Mechanisms for reducing the transpiration component of ET are generally associated with reduced CO₂ uptake, so that there is a trade-off between decreased transpiration and yield. Stanhill (1968), in discussing the strong links between crop water transpiration and growth, states that to decouple the two, either by reducing transpiration or increasing dry matter production, will require a major research effort.

Evaporation. Evaporative losses from a partly or entirely bare soil are an important source of water lost until a full plant cover is established. These losses are therefore greatest during a fallow period. An example of the amounts involved is provided by Luebs (1983). Evaporative losses from a bare sandy loam soil, in summer, totalled over 620 mm for an 85-day period, in a winter-rainfall semi-arid area (southern California). The soil contained water to field capacity at the beginning of summer. A fine, montmorillonitic clay loam, under similar conditions, lost 35% less water through evaporation than did the sandy loam over the same period.

Singh and Russel (1979) estimated that direct evaporation (E) from the soil, for a sorghum crop growing on an Alfisol, was 21% of the total seasonal available water during the monsoonal season, and 23% during the postmonsoonal season. Losses from E in Mediterranean environments, as estimated by French and Schultz (1984) were higher, namely 30–60%.

Water losses from bare soil during summer fallow in a summer rainfall area will be discussed in Ch. 16.

Many dryland crops do not provide a complete soil cover over a large part of the growing season. As long as the soil surface is exposed to radiation, E from the surface can be considerable. After a plant canopy completely covers the soil surface, ET is predominantly T . Therefore, to maximize the T : ET ratio, early plant growth is important, especially in areas that receive frequent light rainfall (Unger et al., 1988). However, for crops grown on stored water, too vigorous early growth may exhaust available soil water for vegetative growth, resulting in extreme water stress at the time of grain formation (cf. Ch. 15). In general, in dry environments, E is a major factor in soil water loss, therefore the highest T : ET ratios are generally achieved in crops grown under a high level of management (Unger et al., 1988), which maximizes water infiltration and conservation.

In addition to the losses due to E , losses due to run-off can be of considerable importance in semi-arid regions that are characterized by intense rainstorms. Gregory (1988) mentions that up to 60% of rainfall during the monsoon in Central India ran off fallowed Vertisols.

Management practices to control run-off, which can contribute significantly to improving WUE, will be discussed in Ch. 14.

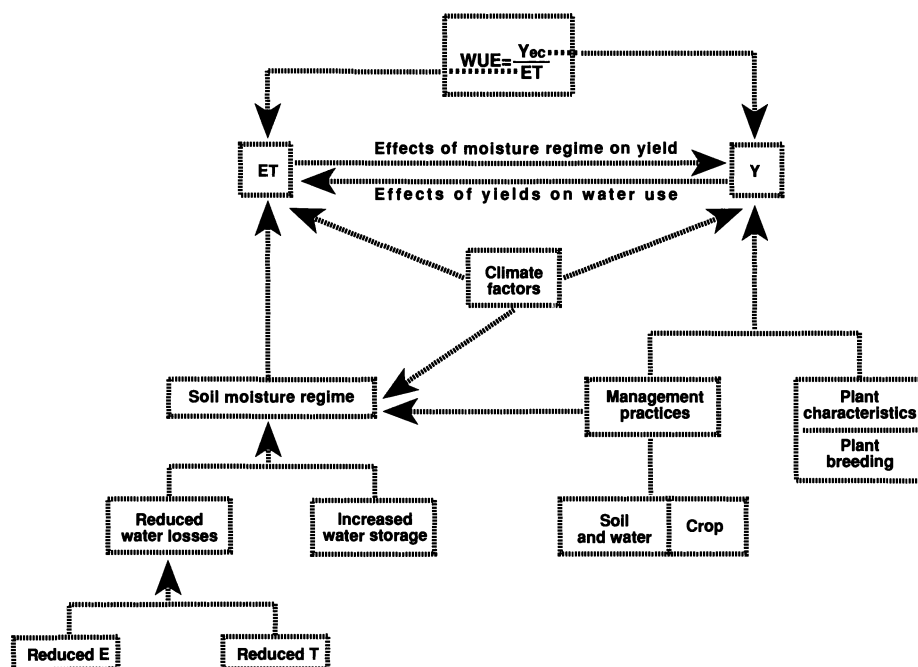


Fig. 5.7. Factors involved in water use efficiency (WUE) and their interrelationships. Y = economic yield and ET = evapotranspiration.

Factors affecting water use efficiency

The complex of factors involved in WUE and the interrelationships between them are shown schematically in Fig. 5.7.

Because environmental factors, management practices and plant characteristics affect WUE by influencing either Y or ET , or both concurrently, practically all the activities of researchers and progressive farmers in the dry regions are aimed at improving WUE.

Similarly, almost all the topics treated in this book have relevance to the subject under review. In order to avoid duplication and overlapping, we will limit ourselves, in the present context, to a brief review of the influence of plant characteristics, environmental factors and management practices on WUE, whilst treatment in depth of these factors will be addressed in the relevant chapters.

The nature of the plant

There are considerable differences in the amounts of water which different plant species use to produce a unit of dry matter.

Plants have developed several processes that enable them to improve their WUE;

most prominent is the evolution of different modes of carbon fixation: C₄, C₃ and the crassulacean acid (CAM) metabolism of carbon fixation. Certain tropical crops have a combination of the Hatch–Slack (C₄) photosynthetic pathway, located in the bundle sheaths which surround the phloem, and the Calvin (C₃) cycle, which is located in the leaf mesophyll cells. This combination appears to be intrinsically more efficient than the C₃ cycle alone, at least under high radiation or high temperatures (Pearson and Ison, 1987).

C₄ plants have a physiological advantage over C₃ plants at higher temperatures and at high light intensities (Ehrlinger and Mooney, 1983).

The very low transpiration ratios of CAM plants is explained by their singular behaviour under moisture stress: their stomata open at night and fix CO₂ in malic acid, causing a gradient with the atmosphere and flux into the leaf. The stomata close during the day, and the CO₂ absorbed at night is assimilated by the C₃ pathway, in the almost complete absence of transpiration (Stanhill, 1968).

CAM plants have the highest WUE, but grow very slowly, since their carbon gain is dependent on the size of the vacuoles for malate storage (Schulze, 1988).

Kassam et al. (1976) report the following seasonal WUEs for rain-fed crops in the warm, seasonally arid tropics and subtropics:

For C₃ crops: 1.2–3.3 g dry matter/kg water (50–130 kg/ha per day).

For C₄ crops: 3.3–6.7 g dry matter/kg water (120–275 kg/ha per day).

Since different crops and varieties grow and expand their canopies at different rates, have different economic yields at different times, and are subjected to different conditions of evaporative demand, WUEs vary between crops having the same carbon metabolism type, and between varieties of the same crop. Examples of these relationships are presented in Table 5.2 (Bunting and Kassam, 1988).

When two crops, such as lucerne and maize are grown for forage under identical conditions, the former requires from four to six times as much water to produce one kilogram of dry matter as does the latter.

Among the plants that are the most economical in their use of water are maize, sorghum and fodder beets; barley, oats, wheat and cowpeas have medium WUE; lucerne has, in relation to the others a very low WUE.

A high WUE is *not* an indication of drought resistance. Lucerne, e.g., is far more drought resistant than maize, which is far more efficient in water use. Even crops, such as maize and sorghum, that have the same C₄ mechanism, and high WUE, show considerable differences in drought resistance, indicating that the resistance is not related to WUE.

Genetic diversity within species, for traits affecting efficient water use can probably be identified in essentially all crop species (Barnes, 1983).

An important factor in increasing WUE is the use of the most highly productive variety available, an example of which is shown in Table 5.3.

TABLE 5.2

Water used, dry matter (DM) produced and WUE of three crops at Samaru, Nigeria (by permission of ICRISAT)

	Pearl millet	Maize	Groundnuts
Crop life (days)	85	117	125
Total water used (mm)	330	486	438
Average daily WU (mm)	3.9	4.2	3.5
Dry matter produced (t/ha)	22.5	19.1	8.4
Average daily dry matter (kg/ha)	264	163	67
WUE (kg DM/kg water)	6.6	3.9	1.7

At all three locations water use by the improved variety was more efficient than that of the traditional variety. The advantage was greatest at the location with the highest average precipitation, indicating that the full potential of the improved variety was dependent on a favourable moisture regime. Even at Lind, situated in the driest region of the USA in which rain-fed wheat is grown, the improved varieties had a higher WUE than the traditional variety.

Climatic conditions

Weather affects both the numerator and the denominator of the WUE formula. The amount of radiation determines the rate of photosynthesis and hence the potential yield, while other components of climate, such as temperature, day length, rainfall, etc., influence vital physiological processes and thereby determine the actual yields. Evapotranspiration is still more drastically affected than are these physiological processes.

Transpiration rates increase almost in proportion to the intensity of solar radiation, whilst in certain crops, of which sugar beet is an example, the rate of photosynthesis increases less rapidly. Certain species may therefore produce more dry matter

TABLE 5.3

Influence of choice of variety on WUE at three locations in the northwest region of the USA

Location	Number of years	Average rainfall (mm)	Average WUE		
			(a) Traditional variety	(b) Improved variety	(b) In % of (a)
Pendleton	46	405	7.04	8.87	126
Moro	65	290	6.20	7.10	115
Lind	55	241	6.60	7.30	111

Source: Adapted from Dryland Agricultural Technical Committee (1979).

per unit of water transpired in a cloudy, humid climate than in a sunny, arid climate (Monteith, 1966).

In the cool, seasonally arid tropics and subtropics, WUEs are comparatively greater by 30–60% than in the warm tropics with a similar precipitation regime, because of the smaller ET, and higher rates of net photosynthesis (Bunting and Kassam, 1988).

Relative air humidity. The lower the relative humidity is, the greater will be the ET. When comparing the WUE of lucerne in a number of locations in the Great Plains of North America, it was found that there was an almost constant inverse relationship between the WUE and evaporation rates. Thus the WUE in North Dakota, with an average daily evaporation rate of 3.98 mm, was almost double that obtained in Texas, where the evaporation was 7.65 mm (Briggs and Shantz, 1913).

Temperature. This factor also affects the WUE. For cool-climate plants, such as wheat and oats, the WUE decreases with increasing temperatures, whilst – within certain limits – the opposite is true for warm-climate crops, such as maize and sorghum.

Soil conditions

The physical and chemical characteristics of the soil have considerable influence in determining WUE. Soil factors determine: (a) the amount of water stored in the soil by influencing infiltration and run-off of surface water, downward drainage and upward capillary movement in the root zone, and (b) the availability of the stored water, e.g. the component available for crop use in transpiration (Stanhill, 1986).

Low soil temperatures can limit water uptake, and therefore reduce transpiration.

Soil moisture content. An inadequate supply of soil moisture has an adverse effect on plant growth and productivity; the same is true of excess moisture in the soil. Both conditions are therefore conducive to low WUE. There is therefore no basis for the assumption that plants grown under dryland conditions will generally be more efficient in water use than the same crop grown under irrigation, or that water stress improves WUE. For each crop and combination of environmental conditions there is a narrow range of soil moisture levels at which WUE will be higher than with a lesser or greater supply of water. Shimshi (1966), working on the interrelationships between fertilization and soil–water–plant relationships, showed that when soil fertility was not limiting, WUE increased when the supply of water to the crop was increased. By contrast, at low levels of fertilizer application, WUE decreased with increasing water supply (Fig. 5.8).

In general, yields of most crops increase when the soil moisture level is maintained as near to field capacity as is practicable. However, the efficiency of water use is

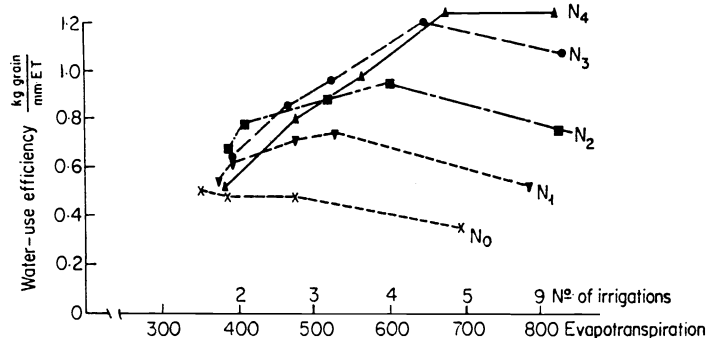


Fig. 5.8. Relationship between soil moisture regime and water use efficiency at five levels of fertilizer application: N_0 =control; N_1 =52.5 kg N ha⁻¹; N_2 =105 kg N ha⁻¹; N_3 =210 kg N ha⁻¹; N_4 =420 kg N ha⁻¹. From Shimshi (1966). By permission of the author.

generally found to be improved at somewhat lower levels of soil moisture (Doss and Ensminger, 1958).

When water is supplied by irrigation, WUE can be strongly affected by the method, timing, amount of water applied, and uniformity of application. For example, drip irrigation can reduce E below that of overhead and surface irrigation methods; however, it also tends to cause salt accumulation. In the absence of sufficient rainfall, periodic or end-of-season leaching by uniform surface irrigation becomes necessary (Loomis, 1983), thereby increasing water use without directly affecting yield.

Salinity. This becomes a problem whenever ET exceeds precipitation; it has the general effect of reducing the availability of soil moisture and increasing plant water stress and stomatal closure. In irrigated agriculture, it may require leaching of salts beyond the root zone, thereby reducing WUE.

Management practices

Cultural practices for high yields usually increase WUE, because the increase in crop yields is generally greater than that of the water use involved. Once the crop covers the soil completely, crop management – with the exception of water supply, has little or no effect on ET. An example of this relationship is shown in Fig. 5.9, and the generalized relationship between yield and soil fertility in Fig. 5.10.

The increases in WUE, resulting from improved management, are due to a decreased E as a fraction of TE; ET efficiency is thereby increased even though T efficiency is little changed, if at all (Fischer and Turner, 1978).

Where water is the major factor limiting crop growth, the reduction or elimination of non-productive water use will increase transpiration, yield and WUE. In rainfed agriculture, this can be achieved by water conservation measures which decrease

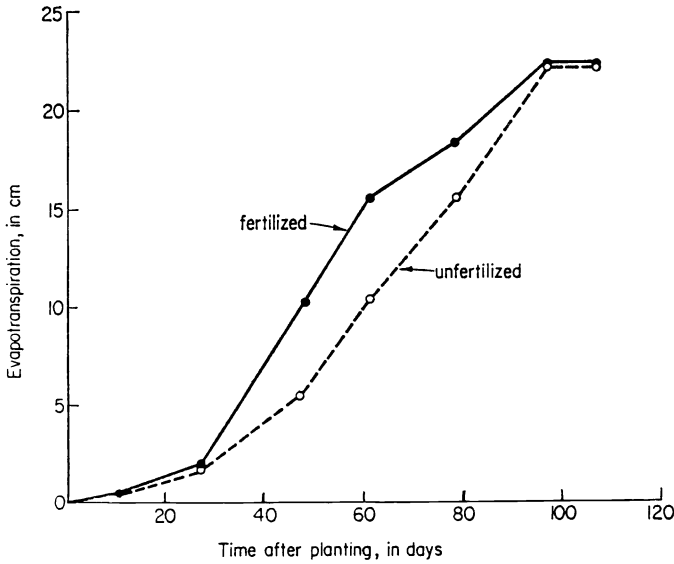


Fig. 5.9. Evapotranspiration from fertilized and unfertilized maize throughout the growing period. The fertilized maize received 157 kg N ha^{-1} . From Linscott et al. (1962). By permission of the American Society of Agronomy, Inc.

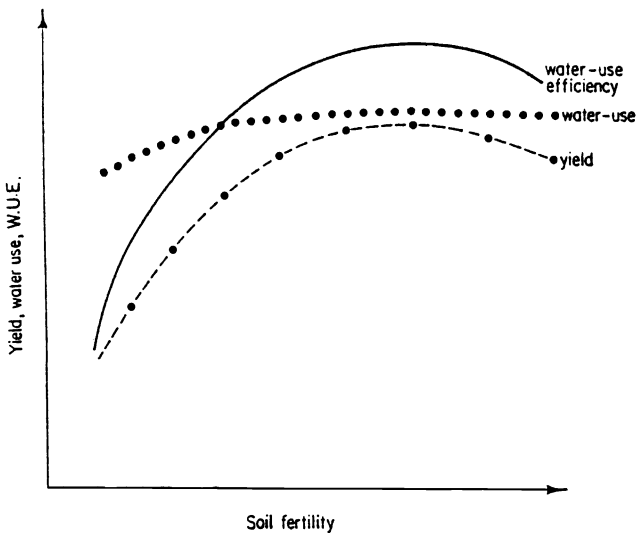


Fig. 5.10. Generalized relationships between soil fertility and yields, water use and water use efficiency.

surface run-off, increase soil water storage capacity, and by tillage practices reducing transpiration by weeds and/or evaporation from the soil (Stanhill, 1986).

Fallow. Under conditions of limited rainfall, devoting one season to storage of annual precipitation is frequently the only way of ensuring one crop every two years.

In Table 5.4 data on the effect of fallow on yields and WUE, as compared to continuous wheat, are presented.

Fallow increased yields at the three locations by 86%, 110% and 157%, respectively; the parallel figures for WUE are increases of 43%, 7.8%, and 29%. This difference in impact of fallow on the two parameters is evidently due to the fact that grain production in the fallow–wheat rotation requires the moisture produced during two seasons, thereby more or less doubling ET. This is one of the few cases in which a management practice that increases yield also has such a marked effect in increasing ET.

In general, fallow is an inefficient way for saving moisture. As little as 10–20% of the fallow year precipitation may remain available to the crop. Most of the water is lost by evaporation, and if weed control has not been absolute, much water is lost as transpiration by weeds (Loomis, 1983).

Planting date. In the dry regions, the optimum time of establishing the crop may have a considerable effect on WUE (in relation to economic yield) by ensuring that the pattern of growth of the crop is adjusted to the pattern of moisture supply.

When sowing in dry soil, considerable time may elapse before rainfall enables germination and crop establishment. If adequate rainfall is delayed beyond the optimum date, yields may be considerably reduced due to inadequate plant development prior to cold weather (in the colder regions) or to a shortening of the growing season in the mild-winter regions.

The introduction of deep furrow drills has made it possible to sow directly into residual moisture, thereby ensuring that planting date and time of stand establishment coincide.

TABLE 5.4

Yield and WUE of winter wheat, grown continuously and after fallow, in the Central Great Plains

Location	Number of years	Average annual precipitation (mm)	Average yields (kg/ha)		WUE (kg/ha/mm rain)	
			Cont. wheat	Fallow wheat	Cont. wheat	Fallow wheat
Akron, CO	60	419	498	1426	1.20	1.72
Colby, KS	49	470	626	1318	1.30	1.40
North Platte, NE	56	495	834	2146	1.70	2.20

Source: Dryland Agriculture Technical Committee (1979).

Plant cover. There is a minimum threshold leaf area index (LAI) value (about 2.5) below which a significant amount of radiation is not intercepted by most crops, with a resultant increase in E ; there is also a maximum threshold (about 12 for sorghum) at which all radiation is intercepted, if plant spacing results in leaves overlapping in all directions. At this level, T is maximized and E approaches zero (Ritchie, 1983).

Disease and pest control. Healthy crops will make better use of available water than crops that are subject to diseases, pests, weed competition, etc. The range of responses to disease, for example, is wide because it may enhance transpiration losses through external mycelium, or reduce water supply by damaging foliage and/or the root system. Insects and nematodes that attack the root system may have a similar effect.

Potential for increasing WUE in dryland agriculture

In dry years, crop management will largely affect WUE by its effect on the rate of water lost through soil evaporation (E), which is largely affected by the amount of incident radiation reaching the soil surface. The rate and extent of crop canopy development will play a major role in the rate of loss through evaporation. Cooper (1983) calculated that in farmers' cereal crops that are poorly managed and as a result have incomplete ground cover, only 20% of ET is actively used as transpiration, and the rest lost through E . Therefore, in dry years or dry locations, WUE can be improved without an increase in water use, whilst in years of greater water supply, improved crop growth will increase the ability of the crop to extract more moisture from the soil (Cooper et al., 1989).

Farming practices have been developed over the years to improve the efficiency of rain-fed crop production under the conditions of limited and variable precipitation that is characteristic of dryland regions.

The data presented in Table 5.5 provide an indication of the measure of success achieved in this respect in the Northwest Pacific region of the USA.

During the period 1953–1974, there has been a marked improvement in yields in all three locations, as compared to the previous 22 years, even though average precipitation was somewhat lower. These increases occurred both in the traditional variety and the improved varieties introduced over the years, a clear indication that management practices had improved markedly.

As the three sources of data are located on experimental stations, one may assume that these management practices represent the state of the art for the periods and locations under consideration.

At Lind, which is situated in the lowest rainfall cereal production region in the USA (Dryland Agricultural Technical Committee, 1979), the greatest increase in WUE was obtained: 98% in the case of the improved varieties, and a very respectable 69% with the traditional variety.

TABLE 5.5

Grain yield, precipitation and WUE in three locations in the NW Pacific

	Yield (t/ha)		Total moisture (mm) ^a	WUE (kg/mm/ha)	
	Trad.	Impr.		Trad.	Impr.
<i>Pendleton</i>					
1931–1952	2.53	2.84	820	3.08	3.46
1953–1974	3.15	4.16	800	3.93	5.20
Increases (%)	24.5	46.5	–2.5	27.6	50.3
<i>Moro</i>					
1931–1952	1.68	1.82	581	2.89	3.13
1953–1974	1.81	2.31	569	3.18	4.05
Increases (%)	7.7	26.9	–2.1	10.0	29.4
<i>Lind</i>					
1931–1952	1.35	1.35	518	2.60	2.60
1953–1974	2.01	2.36	457	4.39	5.16
Increases (%)	48.9	74.8	–11.8	68.8	98.4

Trad. = traditional variety; Impr. = improved varieties.

^aIncludes precipitation during fallow period.

Adapted from Dryland Agricultural Technical Committee (1979).

The low yield levels prevalent in dryland crop production of the developing regions are generally attributed solely to insufficient precipitation, a factor over which the farmer has no control.

The data presented in Table 5.5 indicate conclusively that this fatalistic approach is not justified; acceptable yields and relatively high WUEs can be achieved in dryland production by a combination of improved soil management, better varieties, use of fertilizers, weed control and other agronomic practices.

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CHAPTER 6

Plant Adaptations to Moisture Stress

Definitions and concepts

The ability of a crop to grow satisfactorily in areas subjected to water deficits has been termed drought resistance. The modification in structure and function that increases the probability that a crop will survive and reproduce in a particular environment is termed an *adaptation* (Kramer, 1980). Adaptations can be heritable or not, constitutive or facultative. *Acclimatation* is the ability to slowly adapt to a new environmental condition.

Plants have to contend with three kinds of situations in which they are submitted to moisture stress:

- (a) *Transient drought*. The occasional, transient stress periods at various stages of crop development, a major characteristic of semi-arid regions.
- (b) *Terminal drought*. Causing moisture stress towards the end of the growing period, which prevents normal formation and ripening of grain. This is the most common form encountered in Mediterranean climates;
- (c) *Seasonal drought*. Insufficient precipitation for economic crop production characterizes the arid regions; occurs, generally in cycles, in the fringe areas of semi-arid regions and occasionally in the semi-arid regions.

Categories of drought resistance

Drought resistance has been ascribed to a number of adaptive mechanisms, but there is, as yet, no consensus on the most useful breakdown of categories of drought resistance (Turner, 1986). In many cases, the distinctions are more semantic than substantive. For our presentation, we have adopted the schema shown in Fig. 6.1 adapted from Levitt (1972) and based on three principal ways in which plants can adapt to drought:

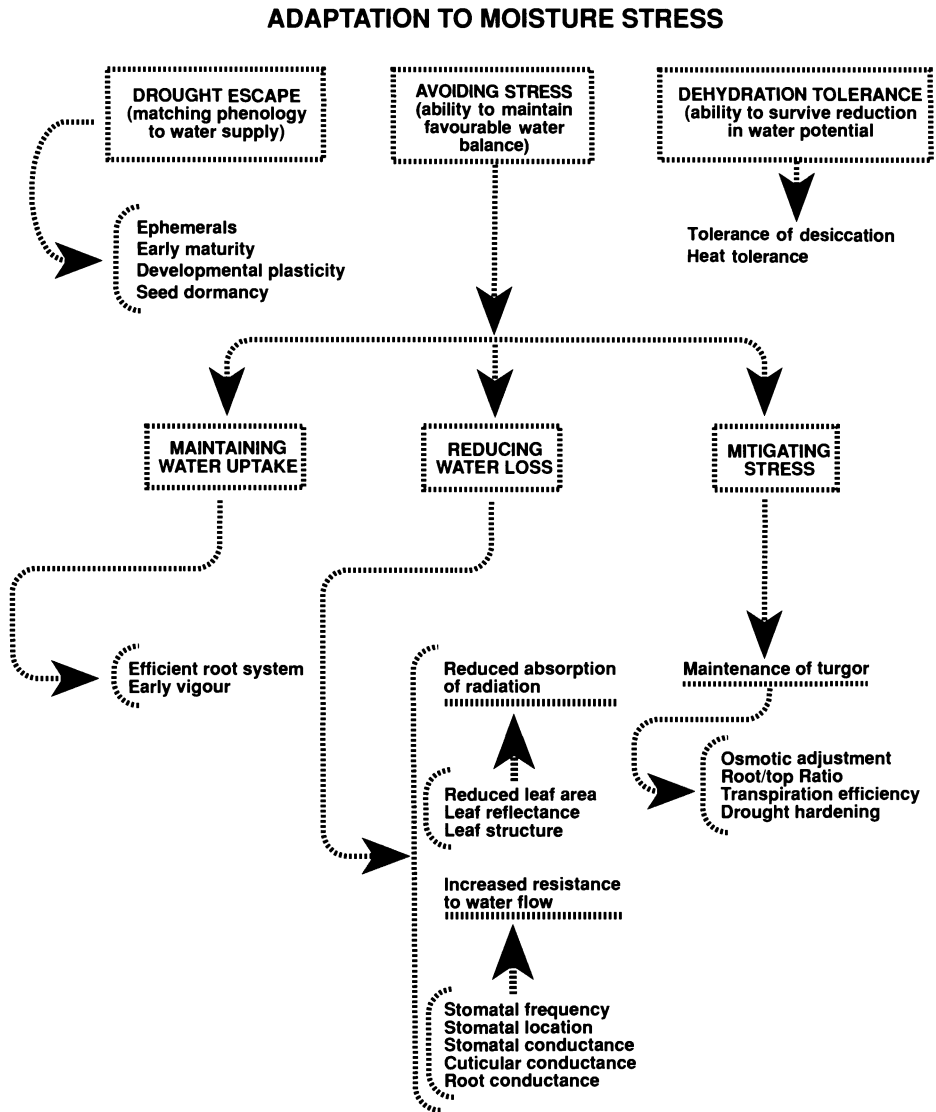


Fig. 6.1. Adaptive mechanisms to drought.

- evading the drought period (drought escape);
- maintaining a favourable internal water balance, thereby postponing the negative effects of drought (drought avoidance);
- surviving relatively long periods of drought (drought survival).

Turner (1986) stresses that not all mechanisms of drought resistance are without metabolic cost to production. He concludes that “only those mechanisms that aided in drought escape, maintenance of water uptake, and maintenance of turgor pressure

did not reduce photosynthesis, crop growth and yield". While it is relatively easy to decide whether a particular mechanism of adaptation affects a short-term process such as the instantaneous rate of photosynthesis, it is much more difficult to determine whether there are long-term consequences of a particular adaptative mechanism.

Many of the traits associated with native plants of the arid regions are concerned with survival; these are rarely, if ever useful to the plant breeder, who perforce, must consider crop productivity as his major objective. Whilst we will review all plant traits involved in drought resistance, this distinction should always be borne in mind. The feasibility of incorporating useful traits for drought resistance in crop varieties will be discussed in detail in Ch. 7.

Drought escape

Matching phenology to water supply

Ephemerals

Evading the drought period is the simplest means of adaptation of plants to desert conditions.

Many desert plants germinate at the beginning of the rainy season and have an extremely short growing period, which is confined to the rainy period. Between germination and seed maturity, as few as five (Polunin, 1960) to six (Kassas, 1966) weeks may suffice. In rainy years these ephemerals may appear in great profusion, but remain dormant during drought years, usually in the form of seeds or fruits.

Early maturity

Only very few crops have such a short growing season that they can be considered similar to the ephemerals in escaping drought. Certain cultivars of millets, that can produce mature seeds within 60 days from germination, are an exception. Even the earliest-maturing cultivars of most crops have longer growing periods and will generally experience one or more periods of moisture stress during their lifetime.

Earliness reduces the number of moisture stress periods, and early maturing cultivars usually avoid terminal stress; it is therefore an important trait. It does not, however, ensure their escaping drought completely, as do the real ephemerals. They therefore need, and usually have, actual drought resistance attributes. In a study with wheat cultivars grown under variable soil moisture regimes, Blum and Pnuel (1990) found that early cultivars tended to have better osmotic adjustment; since the drought stress occurred during the period of ear growth and development, the authors conclude that a greater capacity for osmotic adjustment apparently allowed sustained ear growth under drought stress and the maintenance of relatively larger ears in the higher-yielding cultivars.

In areas with alternate rainy and dry seasons, the ability of a cultivar to achieve maturity before the soil dries out is the main adaptation to drought of cultivated crops, and matching crop phenology to available moisture supply has always been a major breeding objective. There is genetic variability for phenology, and the inheritance is known in many cases (A. Blum, personal communication).

Fischer and Maurer (1978), working with 53 cultivars of wheat, barley and triticale, showed that each day of earliness conferred a yield advantage of almost 30 kg/ha under conditions of terminal stress.

Early maturity, however, generally reduces the potential yield of the crop by reducing the amounts of dry matter available at anthesis and the number of sites for post-anthesis grain filling. Therefore, a reduction of the growing period, as an insurance against drought, is a trade-off for yield.

The degree of earliness required is a compromise to enable the maximum possible production of dry matter before soil water is reduced to a level which will limit reproductive growth after anthesis (Fischer, 1979).

Cavalieri and Smith (1985) studied 21 commercial hybrids and one open pollinated maize cultivar that had been released over a period of 50 years. The most significant factor contributing to increased yield was the lengthening of the grain filling period, achieved without necessitating a longer growing period.

Developmental plasticity

Developmental plasticity is the mechanism whereby the duration of the growth period varies according to the extent and timing of water deficits (Ludlow and Muchow, 1990). Early maturity may be induced by water stress, which is an advantage in dry years; in more favourable years, maturity is delayed and the plant can benefit from a longer growing period. Developmental plasticity matches growth to water availability.

Therefore, whilst the development of early-maturing varieties has been beneficial where seasonal rainfall is predictable or soil moisture levels are known at the time of sowing, phenological plasticity will be more beneficial than earliness, where soil moisture supply is less predictable.

Many crops have some degree of plasticity enabling them to benefit from favourable conditions. Even in an essentially determinate crop such as wheat, e.g., if no drought occurs, and the time to reach physiological maturity is extended, the number of ear-producing tillers, the number of spikelets and florets, and the size of kernels will increase (Turner and Burch, 1983).

Bidinger et al. (1982) found that certain cultivars of pearl millet respond to drought by delayed flowering and by stimulation of secondary tillering. Sinclair et al. (1987) state that cowpeas have an advantage over other grain legumes through their ability to delay development under moisture stress so that flowering and pod formation resume when a favourable moisture regime is reestablished.

Quizenberry and Roark (1976) found that indeterminate cultivars were more pro-

ductive than determinate cultivars of upland cotton under water stress, but the advantage decreased with improved water supply.

Indeterminate growth also has disadvantages. With fresh-market crops, repeated hand-labour harvests are required, and with field crops, a significant proportion of the crop may be lost, damaged, or still be immature before an end-of-season harvest (Loomis, 1983).

Developmental plasticity can be advantageous for genotypes in both modern and subsistence agriculture where unpredictable intermittent water deficits occur (Ludlow and Muchow, 1990). However, the requirements of mechanical harvesting have led to the development of determinate cultivars such as beans, soybeans, sunflowers, thereby foregoing the lower risk advantage of indeterminate cultivars for the sake of the convenience and lower cost in labour in harvesting (Turner, 1986).

Seed dormancy

The seeds of many species that grow in regions with hot, dry seasons, are not able to germinate at high temperatures; they are thereby protected from destruction (EVENARI, 1962). In many desert plants, the process of germination can be stopped and restarted at different stages between inhibition and the appearance of the seedling rootlet and shoot. Seeds may remain soaked and return to a state of secondary dormancy without losing their viability, or they may dry out completely after wetting without losing their germinability (*ibid.*).

The presence of germination inhibitors in such seeds serves as an 'internal rain-gauge', which permits germination only after an amount of precipitation has fallen that will be sufficient to remove the inhibitor (Went, 1952).

As seeds germinate, vacuoles are formed in the cells and their drought resistance decreases very markedly before emergence (ILJIN, 1957).

Avoiding stress

A favourable water balance under conditions of limited water supply can be achieved (a) by improving water uptake sufficiently, so as to replenish lost water (so-called water spenders); (b) by conserving water, i.e., restricting transpiration before or as soon as stress is experienced (water savers); or (c) by postponing dehydration and thereby enabling plants to avoid the effects of stress by maintaining turgor and cell volume.

Maintaining water uptake

Root systems

In xerophytic plants. The drier the environment, the greater the tendency to increase the root system and reduce shoot development: in annual plants of dry, tropi-

cal savannahs, roots may account for 30–40% of total dry matter, whilst the proportion may rise to 90% in perennial desert species, with the roots growing to great depths.

By contrast, annual ephemeral species, that grow during short moist periods, as and when they occur, or in depressions in which water has accumulated, have poorly developed root systems (Fitter and Hay, 1987).

In cultivated crops. Vigorous root systems are associated with drought tolerance. Blum et al. (1977) reported heterosis in the root systems of sorghum hybrids similar to that in vegetative growth and grain production. Root heterosis was expressed by faster growth rates, increased root length, and increased root volume. Gul and Allen (1976) reported that rapid emergence was associated with a faster developing root system.

In crops with a shallow root system, such as upland rice, drought resistance has been improved by genetic root extension (IRRI, 1982).

Where water remains in the root zone at maturity, greater rooting depth can contribute to increased productivity. Where the soil water at rooting depth is not replenished between crops, greater rooting depth would be of little or no advantage (Bremner et al. 1986).

Using a crop simulation model to assess the consequences of deep rooting in sorghum over a 30-year period, Jordan et al. (1983) found that the simulations indicated that deeper root systems increased yields by 20% in about one-third of the years. No effect was evidenced in wet years, when water was not limiting, or in very dry years, when there was no water in any case in the deeper soil profile.

Passioura (1983) has questioned the advisability of breeding for greater root depth, in particular for situations in which crops extract all the available soil water. He argues that the water transpired to create the greater root biomass may offset the extra water gained. Furthermore, the requirements for root growth and maintenance would be at the expense of assimilates which might have been used for above-ground growth and which eventually might contribute to yield. Passioura concludes that in situations where the roots extract all the available water from the soil every year, selection for a smaller root system, particularly in the top soil, might actually improve yield.

The benefits of saving expenditure on assimilates by reducing rooting depth would appear to be minimal, in view of the small biomass of the roots, which constitutes a very small fraction of total biomass produced by a plant.

Ludlow and Muchow (1990) suggest that more benefit could be derived by aiming for a root system with fewer surface roots and more of them deeper in the soil. They conclude from the conflicting results described above, that in situations of intermittent stress, greater root activity would improve stability by slowing the incidence of water deficits and even by reducing their incidence. In a terminal stress situation, greater root depth and density would be undesirable: by increasing the risks of de-

pleting available soil water early in the season, water stress would limit economic yield, or even prevent its formation.

Passioura (1976) describes how the dual root system of temperate cereals resolves these problems by exercising control on the rate of growth of the shoots in accordance with water availability. When the upper soil layer is wet, nodal roots develop quickly, water supply to the shoots is favourable, resulting in rapid growth; when the upper soil layer is dry, the seminal roots, which penetrate deeply, supply water to the shoots from deeper layers in the root zone; the seminal roots have relatively high resistance to flow, thereby causing a slight drop in leaf water potential, decreasing stomatal aperture and CO₂ uptake and resultant slower growth. The plants are smaller, but show no obvious signs of water stress.

The continued exploration of the soil by roots as soil water content decreases and mechanical impedance increases, is due to osmotic adjustment which prevents a decrease in turgor pressure of the root cells (Turner, 1986).

Considerable genetic variation in rooting systems has been reported in sorghum, soybeans, and wheat (Ludlow and Muchow, 1990). Root growth is also indirectly under the influence of genetic factors not related to root growth. For example, Blum and Arkin (1984) have shown that genes that control plant maturity of sorghum affect root growth rate and root length and density.

Though the root system is of considerable importance to all aspects of plant growth, development, productivity, and survival, the study of root systems has been relatively neglected; with very few exceptions, "roots are ignored in actual breeding and selection practices" ... "root systems have been the last morphological frontier" (Jensen, 1988). The main reason for this neglect is the difficulty and cost involved in investigating physiological processes in the below-ground parts of the plant.

Breeding for the improvement of the root system would benefit considerably if marker traits could be found making indirect selection possible.

An ingenious marker screening system was devised by Robertson et al. (1985): by banding a herbicide at different depths and lateral distances from the rows, visual leaf systems of herbicide damage indicate the rapidity and extent of root development.

Summarizing available information, Evans (1983) concludes that the most useful system in practice, over a wide range of environments, would probably have the following characteristics: (a) a deep root system which is also efficient in extracting water and nutrients from the surface layers; (b) does not invest a high proportion of total dry weight of the plant in its roots; and (c) has the ability to readily produce new root axes.

Hydraulic conductance. The roots may develop sufficiently to maintain water uptake adequately, but for this to benefit the whole plant, the hydraulic resistances within the plant must be low enough for the water to be available to the major metabolic centres in the shoot. This topic will be addressed in another section (cf.p. 240).

Early vigour. For cereals grown in the tropics, the yield potential is largely set during the first two to three weeks after sowing. Hence, rapid development of the young plants, with increased radiation interception, should be a favourable trait (Rawson and Hindmarsh, 1983). It would, however, be an undesirable trait for crops grown on stored moisture, as it would lead to early exhaustion of soil moisture supply (Ludlow and Muchow, 1990).

Reducing water loss

The most common way plants regulate water balance and maintain turgidity is to reduce water loss. Several mechanisms are possible, which can be grouped as (a) reducing absorption of radiation, and (b) increasing stomatal, cuticular and root resistance.

Reduced absorption of radiation

Reduced leaf area. The principal means of reducing water loss by xeromorphic plants is their ability to reduce their transpiring surface.

(1) *Shedding of leaves.* Apart from the common means of keeping the aerial parts small, a more extreme adaptation to dry conditions is the shedding of leaves, as in *Fouquieria splendens* (Shields, 1958) and species of *Euphorbia* (Kramer, 1959).

Many desert species, such as *Artemisia herba-alba*, have two kinds of leaves – large winter leaves that are shed at the end of the rainy season, and very small summer leaves which replace the large ones (Zohary, 1961).

Leaf shedding strongly affects root/leaf ratios and the carbon balance of plants. Generally, nitrogen is recovered before abscission (Schulze, 1988).

Krieg (1983) points out that the plasticity of leaf area development is a useful trait allowing plants to conserve water during the vegetative stage so that it can be used during seed formation. He, however, stresses that excessive reduction in leaf area will impose an irreversible limitation on yield, due to the close association between leaf area and seed number in most determinate crop plants.

Whilst the mechanisms for reducing leaf area described above enhance survival by conserving water, they are detrimental to productivity in cases of transient water stress, when water again becomes available. Maintaining leaf area, up to a leaf area index of about 3, is a trait contributing to yield; the lower radiation interception and reduced transpiration rates resulting from mechanisms for reducing leaf area produce the opposite effect.

Therefore, leaf area reduction is a desirable trait in terminal stress situations, because it decreases the probability of the crop running out of water before reaching maturity, and undesirable in the opposite situation, namely, transient water stress (Ludlow and Muchow, 1990).

(2) *Leaf movements.* The simplest form of reduction of leaf area is the *rolling*, *folding* and *wilting* (floppiness) of leaves at times of water stress. These leaf movements help reduce the heat load and water loss.

The rolling of leaves has been shown to reduce transpiration by almost 55% in semi-arid conditions, and by 75% in desert xerophytes (Stålfelt, 1956).

Certain genotypes of sorghum and maize, when subjected to severe stress, will roll up and look as if in very serious condition; two or three days after adequate moisture again becomes available, the plants resume growth. This useful trait for plants grown under conditions of intermittent drought has been named 'latente' (Johnson, 1980).

In crop plants, rolling, folding, and floppiness of leaves should contribute to yield stability in environments with intermittent drought, by enhancing the chance of plant survival until the next rains. These leaf movements do not occur excepting in stress conditions and are reversible, so that photosynthesis returns to normal after the stress is relieved (Turner, 1986). Therefore, no yield penalty is to be expected (Ludlow and Muchow, 1990).

Blum and Sullivan (1986) advocate delayed leaf rolling before heading, in sorghum, as a selection criterium for osmotic adjustment.

(3) *Active leaf movement.* Active leaf movement is an adaptation to both low and high light intensities. For plants growing in weak light, leaf movement follows the sun to ensure maximum illumination; in plants growing in high light intensities, leaf movement reduces the heat load on the upper leaves, and maximizes the amount of light that reaches the lower leaves (Fitter and Hay, 1987).

A special case of leaf orientation is the active leaf movement commonplace in Cucurbitaceae, Leguminosae, and others. When water supply is adequate, the leaves are oriented perpendicular to incoming radiation: thus maximum photosynthetic rates are assured, but water loss is high. When stress occurs, leaves orient parallel to incoming radiation, thereby reducing heat load and transpiration. Indirect light is still sufficient for photosynthesis (Schulze, 1988).

For example, under conditions of extreme drought and intense sunlight, bean leaves orient themselves parallel to incoming light, and follow the sun in that position. This is a reversible process, and by morning the leaves have returned to their normal position (Halterlein, 1983).

(4) *Leaf reflectance.* The reflectance of a healthy leaf increases as it loses water. In maize and soybeans, e.g., Sinclair (1968) found that reflectance was not appreciably affected in the early stages of drying, but increased markedly below 80%, at all wavelengths, and especially in the infrared bands. Cotton behaved in a similar way (Thomas et al., 1966).

Leaves of different species differ considerably in the amount of visible light they reflect. Increased reflectance alters the energy balance of the leaf (Schulze, 1988). It reduces leaf temperature, leaf-air vapour pressure difference, and hence water loss. Photosynthetic rate can be significantly increased, especially if temperatures are above the metabolic optimum (Ehleringer and Forseth, 1980).

The reflectance is caused by the presence of epicuticular wax (Ludlow and Muchow, 1990). Besides increasing reflectance, the wax also lowers epidermal conductance (Blum, 1975) and transpiration, thereby increasing WUE.

Hull et al. (1978), using a scanning electron microscope analysis of the epicuticular wax on the leaves of Lehmann Lovegrass, found that all lines had a basic type of wax, but drought-resistant lines had an additional layer of large wax plates. The authors suggested that wax morphology could serve as a selection tool for increasing drought tolerance in Lehmann Lovegrass.

The maximum yield gain under drought stress of bloomed or glaucous cereals over non-bloomed or non-glaucous was found to be – in wheat: 7% (Johnson et al., 1983); in barley: 16% (Baenziger et al., 1983); in sorghum: 15% (Jordan et al., 1983).

Ludlow and Muchow (1990) conclude from the foregoing that the yield advantage of genetically increasing the epidermal wax coating of an already bloomed or glaucous cultivar would probably be very small.

(5) *Leaf structure*. Various morphological characteristics of leaves help to reduce the transpiration rate and may affect plant performance and even survival under drought conditions: leaves with thick cuticles, waxy surfaces, sunken stomata, the presence of spines, hairiness, etc. are common and effective.

The small, thick, evergreen leaf is one of the most characteristic features of adaptation to dry habitats in Mediterranean-climate vegetation. This thick structure appears to have both beneficial and detrimental aspects. Benefits are the ability to restrict water loss and to delay the onset of drought stress. Detrimental is a simultaneous restriction of CO₂ uptake (Dunn et al., 1976).

(6) *Pubescence*. In certain species, drought stimulates the production of epidermal hairs (Shields, 1958). The mere presence of pubescence is no longer considered as an advantage in reducing transpiration (Kramer, 1959) unless it be through increasing the albedo. However, at high humidity, some desert plants are capable of absorbing water through epidermal hairs (Shields, 1958).

In cultivated plants, the evidence is not consistent. Burton et al. (1977) found that smooth-leaf lines of pearl millet had reduced transpiration (8.9–35%) as compared to near-isogenic hairy-leaf lines. The differences were partly attributed to the ability of the smooth leaves to accumulate more dew; and the authors suggested that the smooth-leaf trait was potentially useful for increasing WUE and drought tolerance. By contrast, Ghorashy et al. (1971) reported that soybean isolines with dense leaf pubescence had significantly lower transpiration rates than glabrous isolines.

(7) *Awns*. Awned cultivars of wheat predominate in the drier and warmer regions, and have been found to yield better than awnless cultivars, especially under drought conditions, though there are exceptions. Awns have chloroplasts and stomata and so can photosynthesize; it has been found that the contribution of the awns to the total dry weight of the kernels was 12% of that by the entire plant (McDonaugh and Gauch, 1959).

Blum (1985) measured carbon exchange rate (CER) and transpiration in a number

of cultivars of hexaploid and tetraploid wheats as well as six-rowed and two-rowed barleys. Awns contributed about 40–80% of total spike CER, depending on the species, but only 10–20% of spike transpiration. The transpiration rate was lower by several orders of magnitude in the awns than in flag leaves and glumes. Blum concludes that “a large amount of awns in the ear is therefore a drought-adaptive attribute in these cereals, for which tetraploid wheat exceeded hexaploid wheat and six-rowed barley exceeded two-rowed barley”.

Increased resistance to water flow

Mansfield and Davies (1981) have called the rapid response of stomata to change in air humidity “as the first line of defence” of plants, the second line of defence is the closure of stomata in response to lowered soil water potential.

Current thinking is that the mechanisms whereby stomata respond to different weather and soil moisture conditions consist of a feedback mechanism governed by the water content of the plant, and a ‘feedforward’ mechanism coupled to the water content of the atmosphere (Stanhill, 1986).

Stomatal number and location. A small number of stomata can retard the development of water deficits. Some desert plants have less than 100 stomata per cm² as compared with averages of 10 thousand per cm² in mesophytes (Killian and Lemée, 1956). In many drought-resistant species (e.g., *Retama raetam*) the stomata are located in depressions in the leaves, which is a feature that can further reduce transpiration by limiting the impingement of air currents.

In crop plants, Dobrenz et al. (1969) reported that drought-tolerant clones of blue panic grass had fewer stomata per unit leaf area than susceptible clones. Similar findings were reported for barley by Miskin and Rasmusson (1970).

Reduced stomatal conductance. Under conditions of water stress, stomatal closure may effectively reduce transpiration. Two responses need to be considered: one to air humidity, the other to soil moisture. Both responses also affect photosynthesis, and there is therefore a cost in saving water by stomatal closure (Schulze, 1988) that may eventually lead to drought-induced starvation (Levitt, 1972).

Various stomatal characteristics, such as low conductance, high sensitivity to leaf water status and saturation deficit, as well as abscisic acid accumulation, have been proposed as desirable traits to improve drought resistance in crops (Jones, 1987). All these characteristics postpone dehydration.

In contrast to the irreversible effects of reduced leaf area described in a previous section, reduced stomatal conductance, being reversible when the stress has abated, can be useful either in reducing water loss or improving productivity.

The lower conductance of the stomata improves yield stability by reducing water loss and reducing the risk of water supply exhaustion before maturity. The drought resistance of sorghum and certain varieties of maize and groundnuts has been attri-

buted, at least partly, to the ability of stomata to resume their normal functioning after a period of water stress (May and Milthorpe, 1962).

An interesting observation made in the course of trials on the effects of soil moisture regime on different wheat varieties, was that the stomata of a semi-dwarf variety remained open throughout the day, while those of the tall variety were open for only a few morning hours, remaining closed thereafter even under favourable conditions of soil moisture and transpiration (Shimshi and Ephrat, 1975).

All the mechanisms for water loss control described above, involve a trade-off between reduced water loss and reduced photosynthesis.

Ludlow and Muchow (1990) conclude that "this trade-off could be acceptable for subsistence agriculture in intermittent stress environments, if it prevents crops from dying before the next rain; and in terminal stress environments, if it prevents exhaustion of soil water before maturity. We believe, however, that the cost of these traits is high for comparable environments in modern agriculture".

Genetic variability for various stomatal characteristics has been established (Jones, 1987). Ludlow and Muchow (1990) consider the use of stomata traits as selection criteria as premature, notwithstanding their potential benefits.

Reduced cuticular conductance. When stomata are closed, the main pathway of water loss is through the leaf cuticle, and the rate of loss is determined by the saturation deficit of the air.

Plants in dry habitats usually have thicker cuticles than those growing in moist conditions. The cuticle consists of a hydrophyllic framework, in which wax platelets are embedded. Under conditions of high humidity this framework absorbs water and swells, thereby separating the wax platelets and increasing the permeability of the cuticle (Van Overbeek, 1956).

The efficiency of a cuticle to reduce water loss may not necessarily be determined by its thickness, but more by the chain length of the lipids forming it (Schulze, 1988). For example, the cuticle of onion scales withhold water more effectively than the thick cuticle of an orange fruit (Schonherr, 1982).

Low epidermal conductance delays leaf dehydration and therefore promotes leaf survival (Sinclair and Ludlow, 1986). Because water loss through the cuticle is significant only when the stomata are closed, low cuticular conductance has no adverse effect on photosynthesis and does not reduce yield potential. It should therefore enhance plant survival in intermittent stress environments without any cost in performance (Ludlow and Muchow, 1990).

Reduced root hydraulic conductance. Higher root resistance effectively lowers leaf water potential during periods of high evaporative demand, and plant growth and total crop water use during vegetative growth is thereby reduced. Limiting growth during the pre-anthesis period reduces the risk of complete crop failure due to early depletion of available soil water (Jordan, 1983).

Passioura (1977) suggests that decreased root hydraulic conductance could be a useful trait for plants growing on stored soil water. By restricting the water extraction by young roots, more water would remain available at later stages of growth when the plants are especially susceptible to water stress.

Richards and Passioura (1981) considered three ways of increasing flow resistance through the upper levels of the seminal root system: decreasing the number of flow axes, decreasing the diameter of main xylem vessels, and replacing these by a multiplicity of smaller vessels.

Their experiments indicated that the most promising approach was decreasing vessel diameter. It was found that xylem vessel diameter was under multigenic control and heritable. A decision was made to initiate a breeding programme for this trait in wheat for dry Australian conditions.

Richards (1987) has shown that in dry seasons, wheat lines with small xylem vessels in the roots, yielded more than those with large vessels, and the small vessels had no adverse effect in wet seasons. This trait can therefore increase yield stability. The trait is heritable, and shows genetic variability.

Mitigating stress

Certain adaptations to drought permit the plants to maintain a high internal water potential in spite of the stress. They are thereby able to maintain cell turgor and growth, avoid secondary drought-induced stress, as well as direct and indirect metabolic injury due to dehydration (Levitt, 1972).

Maintenance of turgor

Many biochemical, physiological, and morphological processes in the plant are sensitive to leaf turgor; therefore maintenance of turgor in spite of leaf water deficits is a major factor in mitigating stress (Turner and Burch, 1983).

Osmotic adjustment. Osmotic adjustment (also called osmoregulation or turgor regulation) is an adaptive process which enables a plant to lower its internal water potential in response to water stress. This is achieved by increasing synthesis and accumulation of osmotically active substances, such as sucrose, a process that lowers the osmotic potential and helps to maintain turgor of both shoots and roots. The improved turgor allows stomata to remain open at progressively lower water potentials and growth to continue, although at progressively reduced rates (Ludlow, 1987).

Osmotic adjustment can therefore be regarded as a tolerance mechanism (Radin, 1983). Begg and Turner (1976) even consider it to be the most important tolerance mechanism, though it is not present in all crops (such as soybeans and cowpeas).

Genotypes of wheat and sorghum with high osmotic adjustment produce more roots, greater root density, and extract more water, especially from the lower soil

profile (Morgan and Condon, 1986; Santamaria et al., 1986). As a result, dehydration avoidance is enhanced.

Osmotic adjustment contributes to grain yield in drought stress situations by maintaining or improving harvest index (Ludlow and Muchow, 1990) by one or more of the following effects:

- improved tiller and floret survival and improved seed set (in wheat: Morgan, 1984);
- improved head exertion and reduced spikelet abortion (in sorghum: Santamaria et al., 1986);
- increased assimilate supply during grain filling, by reduced leaf senescence and by maintaining photosynthetic activity of remaining leaves (Santamaria et al., 1986);
- continued root growth and thorough soil moisture extraction (Sharp and Davies, 1979).

Entries with high osmotic adjustment had the following yield advantages over those with low osmotic adjustment:

- in wheat: increases towards 50% as water supply became more limiting (Morgan and Condon, 1986).
- in sorghum: increases of 15–24%, when drought stress occurred during the pre-anthesis or post-anthesis period, respectively (Santamaria et al., 1986).

Osmotic adjustment can therefore contribute to increasing yield stability under water stress conditions. In trials performed under variable moisture regimes in a Mediterranean climate, Blum and Pnuel (1990) found that the variations in yield among cultivars under drought stress were associated mainly with osmotic adjustment as a major physiological attribute. The authors conclude that since, in this particular case, stress occurred during the period of ear growth and development, a greater capacity for osmotic adjustment apparently allowed sustained ear growth under drought stress and the maintenance of relatively larger ears in the higher-yielding varieties.

Genetic variability in osmotic adjustment has been found in wheat, grain sorghum, millet, rice, cotton, and pigeon pea (Ludlow and Muchow, 1990).

Osmotic adjustment also has its limitations (Turner and Jones, 1980): (a) the degree of osmotic adjustment is limited (in sorghum, e.g., it is limited to the range of –5 to –8 bar); and (b) it does not fully maintain physiological and morphological processes.

Ludlow and Muchow (1990) recommend osmotic adjustment “as a highly desirable characteristic for both intermittent and terminal stress environments in modern agriculture”. Blum (1988) points out that osmoregulation is also effective in plant tolerance to salinity and freezing stresses, both of which involve a component of water deficit. Jordan (1983) is less positive in his assessment; he concludes from his review of plant response to water deficits that “little evidence suggests osmoregulation may play a major role in cultivar difference in drought resistance”. However,

studies since 1983 add support to the importance of the role of osmoregulation (Blum, personal communication).

Root-to-shoot ratio (R/S). For short-term water stress situations, a balance between water uptake and loss can be achieved through stomatal closure; basic adjustments must, however, come through adaptation of the ratio between effective root surface and leaf area (Loomis, 1983).

The root–shoot ratio is a very plastic character; plants under conditions of stress tend to increase the ratio (Fitter and Hay, 1987).

A high root-to-top ratio is a very effective means of plant adaptation to water stress (Begg and Turner, 1976): it is easier for the root system of the individual plant to maintain an adequate water supply to a reduced transpiring surface. Brouwer (1963) gave the name ‘functional balance’ to the way in which adjustments in R/S occur. When there is an ample supply of water, assimilates are monopolized for top growth; with increasing moisture stress, shoot growth is the first to be curtailed whilst photosynthesis and root growth continue, and thus the functional balance is maintained.

The functional balance causes a wide variation in R/S; in wheat, e.g., when moisture is not limiting, roots may account for 10% of biomass, whilst under drought conditions they may amount to 30% (Loomis, 1983).

Transpiration efficiency. Transpiration efficiency (TE) is defined as mass or moles of C or CO₂ fixed per unit of water lost from a *leaf*. This contrasts with WUE of a plant or of crops, which is dry matter produced per unit of water lost (Ludlow and Muchow, 1990).

In principle, there should be no cost for higher TE, and it should contribute to yield potential and stability. Ludlow and Muchow (1990) conclude that “this trait has great promise and potential for increasing yield of crops in the semi-arid and arid tropics”.

Dehydration tolerance (low lethal water status)

Ability to withstand desiccation

The degree to which plant parts withstand desiccation is expressed as the relative water content or water potential at which leaves die; these are called critical or lethal values (Ludlow and Muchow 1990). Tolerance of desiccation is essentially a survival trait; the process which reduces the above-ground phytomass in arid habitats has been called ‘survival by death’ by Evenari (1962).

The leaves of some C₄ grasses, with so-called ‘resurrection’ features, that are na-

tive of the arid deserts of Southern Africa, may remain air-dry for several months and recuperate when water again becomes available (Gaff, 1971).

Desert species have a preadapted stem morphology, so that a certain proportion of the shoots and roots can die without endangering other parts, that can still obtain sufficient water to stay alive.

There are also great differences between different plant organs in their ability to withstand desiccation. Seeds that are filled with food reserves but have no vacuoles can survive very long dry periods, often of many years. Buds of higher plants also have no vacuoles, and are very resistant to desiccation. Certain desert plants survive a degree of desiccation that causes the death of their leaves; but the buds on the stems remain alive and resume growth when the drought ends.

In many species of perennial plants, the above-ground parts die off at the onset of the hot, dry season and the underground parts, such as rhizomes, bulbs, corms, and tubers, remain alive but dormant (Vegis, 1963).

Ability to maintain reserves of water in tissues

Certain xerophytes have water reserves in hypertrophic underground organs which are often greatly swollen. In *Pachypodium bispinosum*, a South African plant, the tubers account for 95% of the total weight of the plant, and contain 91% of its water (Walter, 1962).

Succulents are a special group, frequent in the deserts of North and South America and South Africa, rare in the deserts of Asia and the Sahara, and virtually absent from the deserts of Australia. They tend to be preponderant in arid regions which have short rainy seasons annually (Walter, 1962), being able to survive periods of absolute drought during which they are almost completely unaffected by their environment, both aerial and edaphic. This they manage by living very frugally on reserves of water which they accumulate in their storage organs during periods when water is available in the soil. The amount of water conserved, which can be quite considerable, is estimated at 2000 to 3000 litres for a single plant of *Carnegiea gigantea* (Killian and Lemée, 1956).

Cellular level

The factors influencing the dehydration tolerance of plant tissues are mainly at the protoplasmic level. Differences in cellular structure, protoplasmic composition and viscosity, enzyme activity and water retention properties of the cell wall have been suggested as contributing to survival under water stress (Turner and Burch, 1983).

Protoplasmic dehydration

There are great differences between plant species in their ability to endure desicca-

tion, in relation to both the duration and the degree of dehydration. The more water the plant can hold in its tissues under stress conditions, the greater will be the ability of the protoplasm to withstand permanent injury during drought. The 'bound water'* prevents the proteins molecules of active sites from coagulating (Vaadia and Waisel, 1967). As the tissues become desiccated, the protoplasm becomes increasingly dense and its viscosity gradually increases; when dehydration is severe, complete gelation of the protoplasm occurs and finally it may become rigid to the point of brittleness (Levitt, 1972).

Significance of survival for crop plants

Turner and Burch (1983) point out that "survival of severe stress is less important in crop species than in natural communities, because crops that are severely stressed usually yield poorly", a subject that will be addressed in more detail in the following chapter. Seedling survival and survival in the vegetative phase may be important in situations where the probability of rainfall increases with the life of the crop, i.e., prior to flowering or fruiting (Johnson, 1980).

Low lethal water status influences survival, but has no direct effect on yield components. It is suited to intermittent stress environments, because it helps leaves and plants to survive until the next rainfall. There is genetic variability in a number of cultivated plants, but heritability of the trait has not been determined (Ludlow and Muchow, 1990).

Complex drought resistance mechanisms

In the previous sections various mechanisms of adaptation to water deficits have been described individually. This was necessary for the sake of clarity and convenience. Under field conditions, it is rare that plants react to water deficits by relying on a single physiological or morphological trait; usually multiple mechanisms are activated at the same time (Radin, 1983). One example is the photosynthetic pathways that have developed in response to drought.

Photosynthetic pathways and drought resistance

The C₄ and CAM pathways are mechanisms of ecological adaptation; the latter even enables survival under extreme climatic conditions, at least in certain plants.

* Bound water: due to the presence of hydrophilic colloids, a fraction of the water in the tissue is so tightly held, that the energy of the water molecules is apparently reduced to such a low level that other properties are also changed. This fraction is called 'bound water' (Currier, 1967).

The adaptive advantage of the C4 pathway is especially great under conditions of short and irregular periods of rainfall, frequent diurnal and seasonal water stress, high light intensity, high day temperatures and evaporative demand, i.e., typical hot semi-arid climate conditions. This explains why the major concentration of C4 plants is in the semi-arid tropics and subtropics, where they have apparently evolved as an adaptation to hot, dry, and possibly saline conditions (Ludlow, 1976).

Where net photosynthesis is not limited by environmental and physiological factors, C4 grass leaves are not light-saturated at mid-day summer light intensities, whereas leaves of C3 plants are saturated at one-third to half of these values. This response of C4 plants is due to a continual decline in stomatal resistance and intracellular resistance with increasing light intensity. The marked difference between leaves of C4 and C3 plants is gradually reduced as shading increases. C4 plants are not able to survive in heavy shade (Ludlow, 1976).

The optimum temperature range for C4 plants (30–45°C) is considerably higher than that of C3 plants (10–25°C) (cf. p. 67). Under such conditions, the C4 plants derive a substantial advantage from their more efficient trapping of CO₂, which occurs during photorespiration (Huber and Sankhla, 1976).

C4 plants are also highly competitive: under cultural practices that favour C3 crops, various C4 weeds grow very well, while permanent pastures of C4 grasses are almost free of weeds (Black, 1971).

The higher growth rates and water use efficiencies of the C4 grasses aid survival in semi-arid conditions with low, variable and intermittent rainfall, especially if a minimum amount of C fixation is essential for flowering and seed production in annuals or for the formation of dormant buds and reserve materials in perennials. The tolerance of high temperature without adverse effects promotes early flowering and seed maturity (Ludlow, 1976).

Another advantage under drought conditions is the ability of young leaves of many C4 plants to withstand leaf water potentials as low as –100 bar and recover without injury after stress is removed (Ludlow, 1976).

From a review of the literature, Huber and Sankhla (1976) conclude that “the C4 pathway may be looked upon as a complementary mechanism offering selective ecological advantage to the plant”.

Large groups of plants with the CAM photosynthetic pathway have gone to the extreme of keeping their stomata closed almost all day; this adaptation to drought environments is very effective in conserving the water potential of the plants, because relative air humidity is fairly high at night, at the time the stomata are open.

Succulence seems to be a prerequisite for CAM; it provides a high capacity for accumulation of malate in the vacuoles during darkness. This apparently prevents an excess of malate in the cytoplasm, which might otherwise cause a premature feedback inhibition of PEP carboxylase (Ludlow, 1976).

CAM species generally show slow growth rates and low productivity in their natural habitats, i.e., climatic zones where periods of drought alternate regularly with

rainy periods. From this, Kluge (1976) concludes that CAM is not a mechanism for providing high rates of photosynthesis, but rather for maintaining a positive carbon balance during seasons of drought.

Examples are known in which stress caused a shift from C3 to CAM metabolism (Huber and Sankhla, 1976). This shift is apparently regulated, at least partially, by light, temperature, leaf ontogeny, nutrition, and bioregulants.

Differences between C4 plants

Crop species with the C4 pathway may differ, qualitatively and quantitatively, in their drought resistance. Hsiao et al. (1976) have made a detailed comparison of the contrasting behaviour of two major crops, maize and sorghum, under contrasting conditions of adequate water supply and water deficits. The following summary of their findings will serve as an example of how different crops, both with C4 pathway, differ in their drought resistance.

Crop yields, under irrigation and on stored soil moisture, respectively, give an indication of the overall response of these two crops to soil moisture regimes.

Sorghum clearly has a lower yield potential than maize when soil moisture conditions are favourable; under conditions of a more limited water supply, maize yield is considerably reduced and lower than that of sorghum, which is hardly affected. The relative yield reductions due to the less favourable moisture regimes were 54% for maize, and only 9% for sorghum. It should be stressed that the crops grown without irrigation were submitted to extreme drought conditions. The soil, a deep Yolo clay loam, had been fully wetted to a depth of 3 m before sowing, providing a relatively favourable moisture supply which was progressively reduced during the growing period, but was still sufficient for normal grain formation, as evidenced by the relatively high yields produced by the two crops. There is little doubt that under more extreme conditions the differences between the two crops would have been still more striking.

This experimental evidence is confirmed by practical experience in Israel. Sorghum, grown on stored moisture only, produces high yields (up to 4 ton/ha); under the same conditions, maize usually fails to produce an economic crop.

The first advantage of the sorghum is clearly evidenced in Table 6.1, namely, its ability to increase its harvest index under conditions of limited moisture supply, i.e., to increase the proportion of assimilates diverted to grain formation, a trait visibly lacking in maize.

In addition to the more favourable partitioning of assimilates among competing sinks, sorghum has a greater ability than maize to adjust or maintain grain number in water-limiting conditions.

Sorghum is the more 'plastic' of the two crops in reproductive development: should the number of seeds be reduced by drought, this can be, at least partly, compensated for by its ability to form tillers and branch heads freely. Maize, being determinate in

TABLE 6.1

Grain, yields of maize and sorghum at Davis, CA

	Irrigated		Unirrigated	
	yield (kg/ha)	H.I.	yield (kg/ha)	H.I.
Maize (DeKalb XL 22)	11 300	0.47	5200	0.43
Sorghum (Pioneer 846)	8780	0.48	8000	0.55

After Acevado et al. (1979).

its reproductive growth after the ear has reached a certain size, cannot compensate for stress effects on the number of grains by forming new heads.

Panicle formation on sorghum tillers mature later than those of the main shoot, thereby ensuring that all the panicles are not at the same stage of development if and when water stress occurs; maize does not tiller, and therefore does not have this escape mechanism.

When sorghum is planted at a given population density, it can reduce the number of heads per unit area if soil moisture becomes limiting during the early vegetative stage. Maize is obliged to invest all resources in the number of ears dictated by the planting density, and may therefore fail to fill the young grain in case of terminal drought.

In both crops, most of the dry matter for the grain comes from photosynthates produced after flowering. In sorghum, these are mainly supplied by the panicle and the upper leaves. In maize, the main source of assimilates is the five to six leaves at and above the ear node; an additional quantity may be translocated from lower leaves. The canopy structure of maize allows more light penetration to the lower leaves than with sorghum at the same leaf area index. Water stress hastens the senescence of leaves, which progresses from the base of the stem upward, and will therefore have a more adverse effect on maize than on sorghum.

Photosynthesis is more adversely affected by water deficits in maize than in sorghum: stomata of maize begin to close earlier than in sorghum when water is limiting; therefore sorghum should be able to maintain a normal photosynthetic rate for a longer time than maize when water deficits develop.

There is also a difference in the ability for osmotic adjustment in favour of sorghum, which shows full osmotic adjustment under mild but prolonged stress. Osmotic adjustment of maize under the same conditions is apparently not as complete.

Many authors have assumed that a major advantage of sorghum over maize under drought conditions is due to the characteristics of the root systems of the two crops. Though both root systems are about equal in extent, the ratio of secondary to primary roots is twice as great for sorghum as for maize at various stages of development.

From a review of a number of studies, Hsiao et al. (1976) conclude that the evidence indicates that the differences in the root systems of the two crops are of minor

importance in explaining the differences in behaviour under conditions of water deficit.

In conclusion, it can be stated that the advantage of sorghum over maize under drought stress, with minimal adverse effects, is not due to a single overriding character, but to a fortunate combination of many avoidance and tolerance mechanisms which "allow the plant to avoid excessive tissue water deficits and continue growth and development under mild stress conditions and to tolerate desiccation when the stress becomes severe" (Krieg, 1983).

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CHAPTER 7

Crop Introduction and Breeding for Drought-prone Areas

Crop introduction

Introduction service

Thousands of new, improved varieties of the principal crops are developed and released yearly by plant breeders all over the world. Introducing 'ready-made' varieties is the cheapest and frequently the most effective way of replacing inefficient varieties that are used in traditional agriculture. Moreover crop species, introduced into a new region free from their natural enemies, may be far more successful than in their country of origin.

Even for countries with an advanced agriculture, the introduction of improved varieties, as well as of varieties with special characteristics required for breeding work, is an essential part of any breeding programme. For example, not a single agronomic species or major crop plant grown in the USA actually originated within the borders of the country (Hodge and Erlanson, 1955). Even the hard red wheats, of which over 10 million hectares are grown annually in the United States, are derived from introductions. The same can be said of rice, oats, rye, and sorghum, varieties. Outstanding among forage grasses is a wheat-grass introduced from Siberia, while soybeans, providing crops having a value of a thousand million dollars a year in the United States alone, were introduced from Asia. Acala cotton, which has achieved almost worldwide distribution in warm lands, was introduced from Mexico.

One cannot, however, simply 'go shopping' for improved crop varieties. An *introduction service* must be established that is capable of testing introductions for adaptability, disease resistance, and technological suitability, according to scientific procedures. In addition, the introduction of new varieties of crops, if carried out without the necessary safeguards and supervision, may cause untold damage by introducing at the same time pests, diseases, or weeds, that were previously non-existent in the country.

The introduction of new cultivars may cause disease outbreaks. Maize has been grown for over 400 years in Mediterranean countries and was never attacked by the

Maize Rough Dwarf Virus, even though the vector of this disease, the plant hopper (*Laodelphax striatellus*), is endemic to the region, occurring in wild grasses. When new, high-yielding maize hybrids were introduced into Italy and Israel in the 1950's, severe outbreaks of the disease occurred. Incidentally, the Maize Rough Dwarf Virus does not occur in the USA, where the hybrids were developed (Harpaz, 1972).

Seed transmission of diseases is responsible for the transfer of diseases from country to country. Viruses, such as the seed-borne Bean Common Mosaic and Pea Mosaic have been introduced into many countries in which they were formerly absent.

Most agriculturally advanced countries have import and quarantine regulations aimed at preventing the entry of plant diseases and pests. These services are expensive to establish and implement, and their effectiveness may be impaired by political and economic pressure (Walkey, 1985). However, the absence or neglect of these controls can have devastating consequences.

Areas from which introductions should be made

Improved cultivars

Preconceived ideas, based on climatological analogies, can be very misleading. Pragmatic experience in many countries indicates that it would be an unnecessary limitation to confine crop introduction to the relatively narrow limits of homoclimes. For some of the most conspicuous successes of plant introduction in many countries have been with varieties introduced from areas of very dissimilar climate. Conversely, failures have frequently been recorded with introductions from areas of similar climate.

In Israel, for example, excellent results were obtained with potato varieties from Ireland, peas and tomatoes from the United Kingdom, sugar beets and flax from Holland, grasses from tropical Africa, sunflowers from Canada, barley from various temperate European countries, and many others.

Staples (1981) mentions the case of two tomato cultivars: one, Nacarlang, was developed for high-temperature conditions, but was also found to set fruits better at temperatures too low for normal fruit set; the other, named 'Cold Set', that was developed for the cool, temperate short-season regions, was found to be heat tolerant. Subsequently, it was found that some of the best high-temperature tolerant lines that were identified, had been developed in and for cool, short-season areas. Staples assumes that the reason for this apparent paradox is that basic physiological mechanisms are involved in stress tolerance, and mentions greater thermostability of certain enzymes, that may serve a genotype at both high and low temperatures as a possible mechanism.

In many cases, it is sufficient to change the growing season. For example, many crops normally grown in spring or summer in a temperate climate, can be successfully grown in autumn and winter in a Mediterranean environment. Sugar beets, peas, spring varieties of cereals, most vegetables that are sown in spring and/or summer in Europe, do very well when sown during the winter rainfall season in the Near East.

In brief, there is no certain guideline for deciding a priori from which countries successful introductions can be expected. The scientific level of a country and its success in breeding work on a certain crop, are frequently more important criteria than the climate of the country!

Limitations

There are however certain limitations regarding the climatic areas from which introductions can be made; these are mainly due to daylength and temperature.

The photoperiodic response of a crop, or even of a cultivar, which enables it to time vegetative and reproductive growth to seasonal climatic changes (cf. p. 60) can be an obstacle to successful introduction. If a photoperiod-sensitive crop is moved to a different latitude, its development will be out of phase with its new environment; it may continue vegetative growth without flowering, or flower under adverse conditions for fertilization and for grain formation; in extreme cases, it may die if vegetative growth occurs in winter and the plant is susceptible to low temperatures.

In order to reduce the limitations imposed on crop or cultivar introduction by photoperiodic response, a major plant breeding effort has been invested in developing photoperiod-neutral cultivars and hybrids of major importance; considerable success has been achieved in this respect with a number of important crops.

The high-yielding dwarf varieties of wheat, bred at the International Research Centre in Mexico, and whose wide successful adoption is known as the 'Green Revolution', are an example of this approach. In addition to their high yielding ability, these cultivars have been endowed with relative day neutrality, conferring wide adaptability, which has made their adoption possible on a wide scale.

Sorghum is a photoperiod-sensitive short-day plant, native to the tropics, naturally adapted to a fairly limited ecological area. In a 'conversion' programme, carried out jointly by the USDA and the Texas Agricultural Experiment Station, the tall, photoperiod-sensitive, tropical sorghums were converted through a back-crossing technique to short, photoperiod-insensitive cultivars capable of producing grain under a wide range of environmental conditions (Krieg, 1983).

Other examples of successful breeding for adaptation to wide ecological environments are: reducing the requirement for short days for the initiation of tuberization in potatoes; flowering in maize and soybeans to enable their cultivation in the higher latitudes; selection for long days in crops such as winter cereals so as to delay inflorescence initiation until after the frosts, in order to avoid damage to the embryonic ears.

Changing the response to daylength and temperature is also important in order to avoid flowering in crops such as sugar beet, and many vegetables, in which the transition from vegetative to reproductive growth is undesirable. In temperate climates, such crops flower only in the second year of growth; when they are transferred to a Mediterranean climate, for example, these normally biannual crops flower in their first year, making the crop unmarketable.

In a programme of introduction, there is therefore no alternative but to establish

as wide a collection as finances and manpower allow, without bias or preconceived ideas. To keep the scope of the work and expenses within reasonable limits, the first screening for adaptability, disease resistance, etc., should be carried out as rapidly as possible, retaining for more detailed study a limited number of introductions that show the most promise.

For breeding material

In addition to 'ready-made' varieties, an introduction service must supply plant breeders with 'germ plasm' for the improvement of the varieties on which they are working. Sometimes primitive or unadapted varieties, or even wild relatives of the crop to be improved, may be the carriers of a character of which it is desired to be incorporated in the accepted varieties. In former times, material of this kind could best be obtained by setting up an expedition to one of the 'centres of origin' of the crop under consideration. It is in the centre of origin of a crop that, according to Vavilov (1951), one finds the greatest variability and the best prospect of discovering ecotypes with the sought-after characteristics. However, plant breeders in the developing countries of the arid zones do not have to mount expeditions to find the germ plasm they require. Large collections of varieties and 'banks' of germ plasm have been established in a number of agricultural research institutes.

Papers appearing in the appropriate journals, and reports and lists from research institutes, will indicate sources of required germ plasm, and in most cases it will be made available on request without any strings attached.

The most important recent development for agricultural research in general, and plant breeding and introduction work in particular, with considerable significance for the developing countries, has been the establishment of international research centres (see below).

Adoption of new cultivars in developing countries

Policy

A tremendous amount of agricultural research work is being carried out in all parts of the world. The need for research in developing countries can therefore be legitimately questioned. In a country which is struggling to establish a sound economy, which lacks trained personnel and in which the agricultural population is still primitive, research may appear to be a luxury which can be ill-afforded. It may well be asked whether elementary logic does not compel a developing country to concentrate on disseminating and applying knowledge already available in other countries, and which can be found in the numerous textbooks, bulletins and journals that are devoted to agricultural progress – knowledge which is increasing daily at such a pace that it is almost impossible to keep abreast of developments. In other words, should not the available limited personnel with adequate training be devoted to development instead of agricultural research in general, and plant breeding in particular.

This apparent logic is a dangerous fallacy. Experience has shown that without an adequate national research infrastructure, the introduction and adoption of new technologies in general, and of new crops, varieties and germ plasm in particular, cannot be successful.

Problems

Even the best varieties bred are practically useless unless placed under appropriate ecological conditions of nutrient and water requirements, daylength, crop sequence and weed, pest and disease control, while many other factors need elucidation and due consideration. These cannot be determined simply by reading textbooks published in foreign countries, but frequently require appropriate research under local conditions.

However good imported varieties may be, they will in time generally show some weakness which seriously limits their usefulness. This can usually be overcome by an appropriate breeding programme carried out by local scientists working under local conditions.

Sooner or later, emergency situations will develop: an unexpected invasion of insects, an unexplained epidemic of disease or one of the other numerous emergency situations which normally appear in progressive agriculture. These cannot be tackled simply by consulting textbooks or journals, but require teams of research workers who are experienced in their respective professions and fully acquainted with local conditions, who can judge what is desirable to test and adapt to local conditions, and who are able to carry out this work. As a result of increasing specialization, only workers engaged in research in given fields are usually able to keep abreast of developments and to evaluate correctly the potential importance and applicability to their own specific conditions of the results of agricultural research carried out elsewhere.

International research centres

The international centres have given an entirely new dimension to the national research programmes of the LDCs (less developed countries), which have to contend with limited financial resources and a lack of trained personnel, and cannot possibly, on their own, afford the comprehensive research required to solve all the problems faced by their agriculture.

By contrast, the considerable resources, excellent equipment and above all the interdisciplinary teams of high-level scientists attracted to these centres make possible work on a scale and level that cannot possibly be matched on a national scale, except by the richest countries.

A wealth of breeding material, improved varieties and new technological inputs have become available to the developing countries as a result of the intensive research effort of the international institutes. This increases the need and justification for a strengthening of the national location-specific research efforts (see next section).

The impressive results already achieved with the two major cereals, wheat and rice,

is an indication of what may be achieved with other important food crops, such as root crops, tubers, pulses and oil crops, by an interaction between international and national research programmes.

By providing consulting services to governments of LDCs and assigning staff members as residential specialists, the international centres help to plan, organize and implement local programmes. By taking advantage of these services, the national research systems of the LDCs can obtain valuable back-stopping for their own programmes. They get access, rapidly and without undue expense, to much of the basic information that they lack, to technology that is relevant to their needs, to seeds of improved varieties for screening at their regional stations and to genetic material for their breeding work. By orienting the national programmes to adapting the findings from the work of the international centres to their own conditions, so that they can be applied at farm level, rapid progress can be made on many problems with relatively modest resources and a modest research system. In the plant breeding programmes, for example, promising material from the international centres is made available to the relevant national research institutions at early generation stages, so that local plant breeders can make the evaluation and selection on the basis of their local experience and judgement. Therefore, the benefits of the crop improvement programme that can be obtained by different countries will depend on the competence of the national research centres (Cummings and Kanwar, 1974). "The more successful are the International Centres, the more productive is the national research work" (Kislev, 1977).

During the 1970's more than 130 developing countries joined in international networks for testing experimental crop varieties. By 1979, the wheat network involved 115 collaborating countries, the maize network 84, the rice network over 60, and other groups of countries were testing varieties of sorghum, millet, potato, cassava and pulses. Each network created links among the participating developing countries and with the international centres (Hanson, 1979).

However, the ability to evaluate and adapt the technology provided by the international centres depends on the existence of a well-planned, effective national research system in each country, staffed by trained and committed researchers.

National agricultural research services

The so-called Green Revolution might – at first sight – appear to disprove the need for 'own' research. Within a few years, varieties of wheat and rice developed in international institutes in Mexico and the Philippines, respectively, have been transferred directly to large areas, mainly in Asia. The results were indisputably impressive. However, it is not generally realized that the development of the new HYVs (high yielding varieties) of wheat and rice is actually an example of the transformation undergone by the results of temperate zone research before they could be applied to the subtropical and tropical regions.

Even after the genetic work of adaptation was completed, numerous problems

have arisen following the introduction of the new varieties into different ecological situations: susceptibility to disease, lack of adaptation to flooding, problems of consumer acceptance related to quality, etc. All these problems require local adaptative research and plant breeding work.

This is also true for *all* breeding programmes.

Wherever the Green Revolution has been succesful, this success has been the result of the interaction between the work of the international research centres in which the improved varieties originated and research work in the individual countries themselves, aimed at adapting agronomic practices to the new varieties under the prevailing environmental conditions. The Green Revolution has both required and stimulated a considerable strengthening of national research programmes (Johnston and Kilby, 1973).

In a far-ranging analysis of the effects of technology transfer on agricultural development, Ruttan and Hayami (1973) reach the conclusion that "failure of a nation to institutionalise domestic research capacity can result in serious impediments to effective international technology transfer. A major challenge for the developing countries is to develop the scientific and institutional capacity to design and adapt location-specific agricultural technology to the resource endowments and economic environments in which the new agricultural technology is to be employed".

In an intensive study on the subject of technology transfer from developed to developing countries, Kislev and Evenson (1973) specified an international model in which productivity (in wheat and maize production) was related not only to the research programme of the country in question but also to the research programme in other countries located in similar ecological zones. The idea was to determine how much of the research discoveries of other countries could be borrowed by or transferred to the country in question. They found that a country does 'borrow' or benefit from the research findings of other countries, but that the extent to which it does so depends on its own indigenous research capability. The Kislev-Evenson study concluded that countries without the capacity to produce internationally significant research publications also lacked the capacity to benefit from the research findings of other countries.

Ruttan and Hayami (1973) consider that "the most serious constraints on the international transfer of technology are (a) limited experiment-station capacity in the case of biological technology and (b) limited industrial capacity in the case of mechanical technology". These authors distinguish three phases of adoption by one country of technology from other countries. The first phase – *material transfer* – consists of the simple import of new varieties, animals, machines and techniques without orderly and systematic trials. The next stage is *design transfer*, where new introduced crops and varieties, breeds of animals and techniques are recommended to farmers only after orderly testing. Seeds of recommended varieties are propagated through systematic multiplication. The third phase is that of *capacity transfer*, consisting mainly in the transfer of scientific knowledge and capacity. Increasingly, na-

tional research is strengthened – crop varieties and animal breeds are bred locally to adapt them to local conditions, and adaptive research on agricultural techniques is expanded. New and original approaches are developed, which are not necessarily location specific.

To move from the first to the second stage requires an appropriate organization and infrastructure for experimentation; the transition to the third stage is mainly dependent on an adequate force of trained personnel, backed by modern research equipment.

It is essential that developing countries move as rapidly as possible from the first to the second phase. Phase three will usually be achieved gradually, as research personnel gains experience and motivation.

The benefits resulting from indigenous or national research therefore have three components: a direct contribution, a contribution through the acceleration of transfer from other countries and a contribution to other countries.

Breeding crops for drought-prone areas

Drought defined

Breeding crops for drought-prone areas requires an objective definition of drought. Hounam et al. (1975), in a report on drought and agriculture, cited more than 60 definitions of drought, based respectively on soil water and crop indices.

Drought itself is not a uniform concept; the reaction of the plant is different to atmospheric drought and to soil moisture deficiency, and will also depend on the stage of development at which drought occurs.

Atmospheric drought

This is caused by low air humidity, frequently accompanied by hot, dry winds. It may occur even under conditions of relatively high soil moisture (Aamodt and Johnston, 1936). For example, hot, dry winds occurring at the time of earing of wheat may completely kill the young ears, irrespective of the amount of moisture available in the soil. Actually, plants that have grown continuously under favourable soil moisture conditions, are the most susceptible to atmospheric drought.

Soil drought

This occurs when the soil moisture supply lags behind evapotranspiration: it is usually gradual and progressive; plants can therefore adjust, at least partially, to the increased moisture stress.

For the farmer (and the plant breeder), drought signifies that his crop is under stress, because water uptake lags behind water loss, irrespective of whether this is due

to insufficient moisture in the soil, or to the inability of the plant to take up water rapidly enough to replace water lost by evaporation and transpiration.

This disparity between water supply and demand, in the terminology of plant physiology, is expressed as the ratio between potential evapotranspiration (PET) – the demand for water, and actual use of water by the crop (actual ET), which is a function of water supply. Another way of defining the moisture environment is the ratio of actual ET to the maximum rate of ET of a crop grown under optimal conditions of water supply.

Plant water stress is proportional to the rate of reduction in this ratio below a value of 1.0. “The role of breeding for drought resistance is anywhere in the domain where the ratio $ET_{\text{actual}} \text{ to } ET_{\text{maximum}} < 1.0$ ” (Blum, 1988).

Plant breeders working in drought or drought-prone regions, operate under a variety of environmental conditions; the drought stress with which they have to contend is of three basic types: killing, intermittent, or terminal.

A *killing drought* occurs where or when total seasonal rainfall is insufficient for normal development resulting in an economically acceptable yield; this situation is (a) typical for low-rainfall areas, (b) frequently experienced in fringe areas of semi-arid regions, and (c) occurs occasionally in semi-arid areas with adequate *average* rainfall for crop production.

A *terminal drought* is when precipitation enables satisfactory early growth, but is insufficient towards the end of the season, causing stress during grain formation, without necessarily killing the crop. Terminal drought is encountered by crops grown in marginal-rainfall areas, or during the dry season on insufficient stored soil moisture. The crops progressively deplete available moisture; the stage at which terminal stress will occur depends primarily on the depth of wetting of the soil profile, and on management practices that restrict early vegetative growth, so that sufficient soil water remains available to bring the crop to maturity (cf. Ch. 15).

Intermittent drought is typical for rainfed crops grown during the wet season; stress can occur at any stage in growth, from germination to maturity, with various degrees of severity, and can be relieved as and when sufficient rain falls. Unfortunately, the stress periods generally appear at random, so that different growth stages are affected in different years and sites (Barnes, 1983).

Drought resistance defined

Drought resistance of crop plants can be defined in a number of ways:

- the ability to survive under drought conditions;
- the ability to endure drought with a minimum of injury;
- “the ability of one genotype to be more productive with a given amount of soil moisture than another genotype” (Quizenberry, 1982);

- wide adaptability, including the ability to overcome rapidly, or avoid, periods of water stress.

Blum et al. (1981) have stated that “The total drought resistance of a genotype cannot yet be defined physiologically and most probably it does not exist as a single trait”. Schmidt (1983), from a review of literature in this field concludes that: “research reports on various aspects of drought response are sometimes contradictory, difficult to integrate, often based on greenhouse studies, and not of practical usefulness in a plant breeding program where large numbers of lines must be screened”.

The ability to survive

The ability to survive under drought conditions is an essential characteristic of the xerophytic natural vegetation of the arid regions, and the characters involved have been described in Ch. 6.

Typically, these plants have adapted themselves to arid conditions by a reduced transpiring surface resulting in dwarfed plants with very limited total leaf surfaces. However, the farmer is not concerned with the *survival* of the species and varieties he grows; in case of crop failure he can always buy a new supply of seeds from a commercial source. The farmer is concerned rather with the *productivity* of his crops, whilst most of the mechanisms for ensuring survival of xerophytes under drought conditions usually achieve this latter aim by severe restriction of the assimilating surface and therefore at the *expense of productivity*. Typical xerophytic characteristics are therefore not, a priori, necessarily desirable in cultivars to be grown under conditions of limited water supply.

Nevertheless, many attempts have been made to use xerophytic characters as indices of drought resistance for breeding purposes. The osmotic pressure of germinating seeds (Buchinger, 1930), the bound water content of wheat varieties and grass species (Newton and Martin, 1930), viscosity (Schmidt et al., 1940), resistance to artificial atmospheric drought and heat, in drought chambers (Aamodt and Johnston, 1936; McAlister, 1944), etc. All these tests, at best, could serve for screening strains that are more or less capable of enduring drought, but without a proven direct relation to their productive ability.

The ability to endure drought with minimal injury

An early definition of drought resistance is “the ability of plants to adapt to the effects of drought and to grow, develop, and reproduce normally under drought conditions, because of a number of properties acquired in the process of evolution under the influence of environmental conditions and natural selection” (Henckel, 1964).

It will be noted that productivity is not included in this definition, which therefore may be valid for plants in general, but is not suitable for crop plants, for the same reasons mentioned above.

Proportional reduction in yield due to water stress

The criterion suggested by Levitt (1951) and which has gained wide acceptance, is “the ratio of yield under dry conditions to the yield under optimal conditions of water supply”. At first sight, this criterion appears to be most appropriate, as it includes productivity as a basic parameter; however, it only reflects the yield relation of a given cultivar between one season and another, and has no value as a parameter for choice between varieties in breeding or farming practice. An example will demonstrate the fallacy of this definition.

In an experiment in Israel, comprising 16 field tests, the relationship between precipitation and yield of 12 wheat varieties was studied, under a wide spectrum of moisture regimes (from 230 to 755 mm) (Blum and Pnuel, 1990).

In Table 7.1, two contrasting varieties are compared (a) under conditions of moisture deficit, and (b) with adequate moisture. These varieties are: Miriam, bred specifically for drought resistance, and Bethlehem, with high potential yield and wide adaptability (Blum and Pnuel, 1990).

The decline in yield in the low-moisture régime compared to that obtained under favourable conditions is greater for the high-yielding and more adaptable Bethlehem than for the drought-resistant Miriam, confirming the latter's reputation as a drought-resistant variety.

It should be noted that the relatively high yield of both varieties with a rainfall of only 230 mm, is mainly due to the excellent distribution of the rainfall in the two seasons of the trial. Drought stress occurred towards the end of the vegetative period, and sufficient rain fell during grain filling to allow maturation to proceed under favourable conditions. Under greater moisture stress, both varieties would have given far lower yields, and paradoxically, the difference between them would be much smaller, as shown in the results of another trial, mentioned below.

The Northern Negev in Israel is a typical rainfall fringe area and straddles what is called ‘the drought line’, below which the government does not compensate farmers for losses due to drought. Average seasonal rainfall is 239 mm, and its variability has been described in Ch. 1. Based on this variability, and the results of a trial with wheat

TABLE 7.1

Proportional reductions in yields of two varieties

Variety	Yield (kg/ha)		Proportional reduction (%)
	low-rainfall régime (230 mm)	high-rainfall régime (700 mm)	
Miriam	2900	5450	0.47
Bethlehem	2700	6200	0.56

Based on data from Blum and Pnuel (1990).

TABLE 7.2

Estimated cumulative yields of two wheat varieties in the Northern Negev

Precipitation (mm)	Number of seasons	Yields (kg/ha)			
		Average		Cumulative	
		Miriam	Bethlehem	Miriam	Bethlehem
< 200	14	—	—	—	—
200–249	7	1200	1200	8400	8400
250–299	7	2000	2200	14 000	15 400
300–349	1	2700	3200	2700	3200
350	1	3000	3600	3000	3600
Total	30			27 800	30 600

Sources: Blum (1990); Katzenelson (1985).

varieties obtained in 31 location $\times$ year tests, the data shown in Table 7.2 were calculated.

Miriam is a variety with drought resistance, independent of yield potential, widely grown in the Negev. Under conditions of low rainfall, with good distribution, it can produce relatively high yields and outyield other varieties. However, when more severe drought stress limits yields, its relative advantage over other varieties is reduced and may even disappear completely, as in the trials under discussion.

Bethlehem is a variety that was developed initially in a medium- to high-rainfall area; from the F8 generation onwards it was tested concurrently both in the area in which the earlier generations had been selected and in the Northern Negev (fringe rainfall). It was released at the F14, and was designated jointly by the breeder and the Extension Service for sowing exclusively in low-rainfall regions. However, it performed very well in high-rainfall areas, showing wide adaptability. Its relative drought resistance is attributed to the maintenance of high leaf water potential, non-stomatal control of transpiration, and high leaf permeability (Blum et al., 1983a), the highest proportion of awns in the ear and the highest ear carbon exchange rate per unit area at 30°C of all the wheats studied (Blum, 1986).

Conclusion

After reviewing the different definitions of drought resistance used in the literature, their shortcomings and ambiguities, one is led to the conclusion that the most apt, and inclusive definition is that proposed by Blum (1990): “drought resistance involves any plant reaction to water deficit which may develop when potential crop evapotranspiration is not met, even under supplemental irrigation, as the case may be”.

The target environments

The type of drought environment in which crops are grown has relevance to the breeding strategy and breeding methodology adopted. The major environments that the plant breeder is liable to encounter in the dry regions are deserts, fringe semi-arid, semi-arid, subhumid and irrigated areas. These have been described in Ch. 1; the implications for plant breeding will be considered in this section.

Deserts

Under desert conditions, when no additional water resources are available, there does not appear to be much the plant breeder can contribute, excepting possibly improved grasses and shrubs for favoured ecological niches, such as depressions, sabhas, etc.

Where water harvesting or irrigation can be practised, these areas are, in essence, no longer different to those with more favourable moisture régimes to which we will refer later.

Fringe semi-arid areas

These are the areas that correspond to what Blum (1989) has defined as “the domain of net carbon loss”, namely areas where stress is so severe that a net loss of carbon takes place so that plants are merely surviving stress.

Generally, a continuous high moisture stress prevails throughout the entire season. The amounts of water available for production in these fringe areas suffice only for a limited growth period. Therefore, breeding for drought avoidance through early maturity would require shortening the growing season to such an extent that yield potential would be extremely low. Similarly, “little is to be gained from research aimed at increasing tolerance to drought” (Loomis, 1983).

Breeding efforts are futile for crops that are practically under almost constant and severe moisture stress. “Biological immunity to the effects of drought is not a possibility” (Quizenberry, 1982).

At an experimental station in a low-rainfall area of Kenya, with a bimodal rainfall of 700 mm, where the former grazing lands had been converted to arable farming, the plant breeder told me proudly that he had been successful in breeding a drought-resistant maize for a low-rainfall area, and as proof produced a few little runts of cobs with 4–6 kernels. This ‘success’ explained why Government drought relief in the area was necessary in nine years out of ten in order to prevent starvation of the people who raised the ‘drought-resistant’ grain.

With a mean annual rainfall of 700 mm, it might be possible to produce a crop every year, but with the two growing seasons separated by dry periods, each crop received only an average 300–350 mm, and crops failed almost every season.

All the efforts of the experimental station had been devoted to breeding for drought resistance, but no thought had been given to the possibility of increasing soil

moisture by conservation methods, or of growing a single annual crop on the combined precipitation of the two rainy seasons.

Efforts at increasing water supply, under conditions of low rainfall, can give good results. For example, in a summer-rainfall area in Botswana, with a 60-year average rainfall of 465 mm, average yields of sorghum are 161 kg/ha, with a coefficient of variation of more than 120%. Yields of 250 kg/ha are only reached with an above-average rainfall of 500 mm. During droughts, area average yields fail to reach 100 kg/ha. Improved management practices gave approximately five times the average on-farm return (Siebert and Modiakgotla, 1988).

In the Northern Negev of Israel, with an average winter rainfall of 239 mm, and a seasonal evaporative demand of 551 mm, the costs of wheat production using modern methods: mechanization, improved varieties, fertilizers, weed control, etc., are equivalent to a yield of 1.5 t/ha grain. Profitable yields were however obtained in only four out of ten years, using the conventional cropping pattern (continuous wheat). By growing wheat in rotation with fallow, grain increases of 104 to 220% were achieved (Amir et al., 1988).

The conclusion is that below a minimum level of available water economically acceptable yields of grain are not achievable, and that therefore in the low-rainfall areas it is essential to direct efforts to developing and applying methods for increasing available soil moisture and reducing water losses to a minimum. Experience has shown that this can be achieved by conservation tillage, crop-fallow systems, water harvesting, mulches, weed control, etc.

These and other management practices, can create a moisture régime just sufficient to ensure economic yields in most seasons; under these circumstances, drought resistance would become an important trait. The question still arises whether a breeding effort aimed at developing cultivars specifically adapted to relatively low moisture régimes, just sufficient to produce a low-yield crop, is justified or necessary.

Semi-arid areas with adequate average rainfall

We have already pointed out (cf. p. 11) that semi-arid regions are not necessarily areas with inadequate precipitation for economic crop production; their basic characteristic is the alternation of a completely dry season with a rainy season. Annual average precipitation in these areas is above 350–400 mm in winter precipitation, and an equivalent 500 mm in summer rainfall. Adequate average precipitation implies that there will be some seasons with too little moisture for optimal yields, but years of killing drought, i.e., years of crop failure, or near-failure, are relatively rare. In average and above-average years, a favourable water supply will enable a crop to express its full yield potential.

The two major moisture régimes under which arable crops are grown in areas with adequate average rainfall are (a) in a variable and unpredictable moisture environment during the rainy season, or (b) on stored water in the dry season.

Variable moisture environment. Even in years of above-average rainfall, occasional periods of drought occur during the growing season. Plants must be able to take advantage of the periodic rainfall, and to recover quickly from periods of intermittent stress, at whatever stage they occur.

The major objective of breeding plants for cultivation under conditions of intermittent stress is to improve performance and stability under conditions of unpredictable precipitation.

The ability to recover from stress is a function of plant age (Blum, 1988): cellular drought tolerances decrease as the plant develops from seed and initial stages of germination, to juvenile plants and meristems. Therefore late-maturing genotypes and plants with indeterminate growth are more likely to recover than earlier or determinate types.

Turner (1979) lists the following desirable traits for crop plants in this environment: high photosynthetic rates, dense but not necessarily deep roots, and indeterminate growth habits (cf. p. 232).

Quizenberry (1982) states that the variability in seasonal precipitation in this type of environment, the unpredictability of drought periods, and the possible negative relationships between traits for drought resistance and productivity, "may hinder the development of adapted crop varieties and, thereby, reduce the probability of a successful breeding effort".

And yet, it is for crops grown in this kind of situation that the major breeding efforts for drought resistance are justified, and need to be invested.

Stored moisture environment. In all semi-arid regions, whether subtropical, Mediterranean or middle-latitude, crops can be grown during the dry season, completing their entire life cycle, mainly or entirely, on precipitation stored during the preceding rainy season. If the amount of stored water is adequate, only mild transient stress will be encountered at periods of unusually high ET; the only type of severe water stress the crops are liable to encounter, is terminal stress, if the crop is relatively late maturing.

The probable length of the growing season can be estimated from the depth of the soil at, or near, field capacity at the time of planting, so that a major specific breeding objective would be the development of cultivars phenologically adapted to these conditions. If they are too early maturing, yield potential will be sacrificed; if maturity is delayed, yields will suffer because grain formation will occur under terminal stress conditions.

Quizenberry (1982) mentions the following mechanisms available to exploit this type of environment: phenological, morphological, functional and metabolic, and states that "the potential for genetic improvement of drought resistance in this environment should have a high probability of success".

Summary

The drought situations encountered in drought-prone regions are basically of three kinds: killing (seasonal), terminal, or transient (intermittent).

The prospect of successfully developing varieties capable of producing economic yields for environments in which killing droughts are the norm, is, at best, too dubious to justify investments in breeding work for this purpose. All efforts need to be directed towards improving the moisture régime, by water conservation and appropriate management practices.

Where terminal drought which develops towards the end of the growing season is a regular occurrence, major breeding efforts need to be directed to developing early maturing varieties that will evade the terminal moisture stress.

Even in areas or seasons with adequate precipitation, periods of water stress at different stages of growth will frequently occur. It is with these drought situations that plant breeders most need to cope, by developing productive varieties that remain relatively unaffected or recover rapidly from transient drought.

Major approaches to breeding for drought resistance*Indirect breeding for drought resistance*

Indirect breeding for drought resistance is the major approach used in past and present breeding procedures, whereby genetic material is not directly tested for drought resistance, but is exposed to drought stress as well as to other unidentified stresses, as they occur in the course of regular field assessment, during many years of testing at a number of locations. Genotypes that perform well under these conditions, will, perforce, incorporate desirable traits enabling them to avoid or tolerate drought stress at different stages of their development.

It should be remembered that many drought-specific traits have been incorporated into cultivars of important crop plants, either through an evolutionary process of adaptation, or often indirectly, as the result of breeding efforts.

Many plant characteristics might improve plant performance under moisture stress, such as phenological adaptation, developmental plasticity, osmotic adjustment, proper leaf orientation, efficient rooting system, early vigour, leaf area maintenance, increased leaf reflectance, low lethal water status, etc. Provided the trade-off with yield is acceptable, these traits have become part of the genetic make-up of progenies that have consistently shown outstanding performance in field assessment of genotypes, during years of multilocal empirical testing.

Other traits, that are equally useful in improving yielding ability of rainfed and irrigated crops, such as heterosis, high harvest index and others (cf. p. 298) have been

used intentionally in the breeding programmes for rainfed crops, in semi-arid conditions. "In cases where environments are variable mainly in the water regime, stable genotypes could indeed be physiologically classified as drought resistant" (Blum, 1983).

Their relatively good performance under stress is related to what Blum (1988) considers as the 'residual' effect of their high yield potential.

Breeding for specific adaptation or for wide adaptability

A breeding programme for drought-prone areas requires a decision on whether to emphasize yield stability in a specific environment, so that farmers are guaranteed some acceptable – but probably modest – yield in all but the very worst years, or high-yield potential, i.e., maximum yields in good years (Landsberg, 1988).

In practice, this signifies a decision between breeding specifically for drought conditions versus breeding for wide adaptability, i.e., genotypes that produce on average well in a relatively broad range of environmental conditions.

Breeding for specific adaptation

Breeding for different kinds of stress, other than water stress, has been very successful. Screening plants for disease resistance by growing them in sites known to be infested with specific pathogens; for resistance to saline conditions by growing on saline soils; for winter hardiness by growing in winter in cold regions, are a few examples.

The major limitation of field screening specifically for drought resistance, lies in the very large element of chance inherent in selecting for a characteristic that is under complex genetic control, and shows strong interactions with the environment. As already pointed out, drought conditions vary widely in severity and timing, from year to year in the same sites and between sites in the same year. Hanson and Nelson (1980) conclude that "selection in any one drought year will concentrate genes that were valuable just for the type of drought that occurred in that year. It is obvious that continual annual changes in the direction of selection pressure is inevitable with field screening for drought resistance, which makes genetic advance very difficult".

Blum (1989) points out that "selected genotypes that appear to yield well in one cycle of selection may not perform well in the next cycle, because a large fraction of the apparent variation in the population under stress is environmental rather than genetic". Blum concludes that the use of yield as a selection index for drought resistance under drought conditions is inefficient.

Quizenberry (1982) quotes a number of sources that have studied the response of selection for yield to different environments. Their findings indicate that (a) environmental and genetic variances have usually been higher when growing conditions were favourable; (b) heritabilities for yield were higher in an optimal environment; and

(c) the rate of genetic advance through breeding was usually greater in a favourable environment.

The overall conclusion from these findings is that selection for yield should be more productive in a favourable rather than a stress environment.

The most important drawback of specific breeding for drought resistance is that it results in a much lower level of productivity in other ranges of the environment by focusing on the maximum genotypic response to a highly specific factor or factors of the environment (Sneep and Hendricksen, 1979) as shown in the example presented on p. 263.

Cultivars developed by this approach show a very narrow environmental adaptability, while the semi-arid environment for which they are developed is inherently extremely variable.

Location-specific cultivars. In traditional agriculture, the varieties grown are characterized by numerous genotypes which have specific adaptation to relatively narrow ecological niches. These 'landraces' are the result of the farmers' tradition to save seed from the most promising plants and of natural selection pressures rather than of systematic breeding.

An example of the fallacy of the requirement to breed varieties with very specific adaptation is the early introduction and breeding work on wheat which was carried out in Palestine by the present author. By tradition, almost every district in Palestine grew a standard local variety of wheat. These 'land' varieties were remarkably uniform in their respective types, probably as a result of mass selection and adaptation over a very long period. In view of this centuries-old tradition, it was originally thought that the breeding programme should aim at creating improved varieties adapted to the specific conditions prevailing in various districts. In consequence, a large number of selections and crosses were made among native varieties, and a comprehensive introduction programme was initiated. However, after a few years, it became apparent that the views on which this programme were based were not well founded.

In the course of the first six years of work on this crop in Palestine, 51 experiments were carried out at 11 locations, from Dan in the north to Negba in the south, each location being typical of a certain district. The annual rainfall recorded during these trials ranged from 300 to 940 mm; the varieties sown experienced drought, waterlogging and dry, hot winds, the so-called 'khamsins'. The experimental sites were located at altitudes varying from 100 m below to 500 m above sea level, and the soil types on which the experiments were carried out ranged from loess to heavy soil. These trials were therefore representative of most conditions that were likely to be encountered in the country by wheat, and the generalizations drawn from the data could be considered well founded.

The surprise result of these trials was the finding that it was not the 'adapted' varieties that gave the best overall results, but that one or two introduced varieties

were outstanding in almost all trials, notwithstanding the great range of environmental conditions encountered.

From this work, we concluded that the attempt to develop varieties specifically adapted to each of the country's eco-agricultural regions was a waste of effort, and work was directed to introducing and developing varieties as widely adapted as possible.

The conclusions from this personal experience were confirmed by results from various early breeding programmes in the world. Kiesselbach (1951) pointed out that, of the approximately 100 000 inbred lines of maize that had been developed in the USA up to 1950, only 60 were in use for the production of commercial hybrids. Eight of these inbreds, used in various combinations, were involved in the make-up of the most outstanding and widely adapted commercial hybrids. These inbreds had been isolated in a still more limited number of open-pollinated varieties.

In uniform varietal trials carried out in 18 localities in the Near East under the auspices of the International Wheat Programme, the variety Pitic 62 bred in Mexico, yielded close to 2275 kg/ha – about 650 kg/ha more than the average of the 25 varieties tested, and 1300 kg/ha more than the average national yields in that area. Three varieties: Pitic 62, Penjamo 62, and Nainari 60, gave the highest yields in 14 out of the 18 locations. Pitic 62 gave the highest yield in nine locations (Stakman et al., 1967).

The trials were located between 35°N and 17°N latitude and at elevations from about 170 m below sea level to 1700 m above sea level. Soil fertility ranged from low to high; temperature, daylength, and incidence of pests and diseases, varied considerably; at some locations the wheat was rain-fed, and at others it was irrigated. Obviously, the three outstanding varieties and in particular Pitic 62 had a very wide adaptability.

We will return to this subject in the next section.

Of course there are situations which require a specific breeding effort.

A most convincing example is the need to breed very long stalked rice varieties (the so-called floating varieties) in which elongation of internodes keeps pace with rising water levels for areas that are flooded to a depth of 2 m and more.

Another interesting example is that of Hopi maize. In order to reach moist soil at the time of planting, the Hopi Indians dig holes with a planting stick to a depth of 35 cm. Normally, maize could not reach the surface from such depths, but in Hopi maize the mesocotyl is greatly elongated. Hopi maize also develops a single root from the seed which strikes deep into the soil to reach moisture, as opposed to the three seminal roots of the usual maize cultivars (Shantz, 1956).

Conclusions. If the objective is to breed for adaptation to very specific and predictable stress situations, such as salinity, mineral toxicity, soil-borne disease, mineral deficiencies, etc., there is justification for the conclusion that “selection criteria alternative to yield under stress may offer a more direct treatment and effective solution of the problem of selection under stress”.

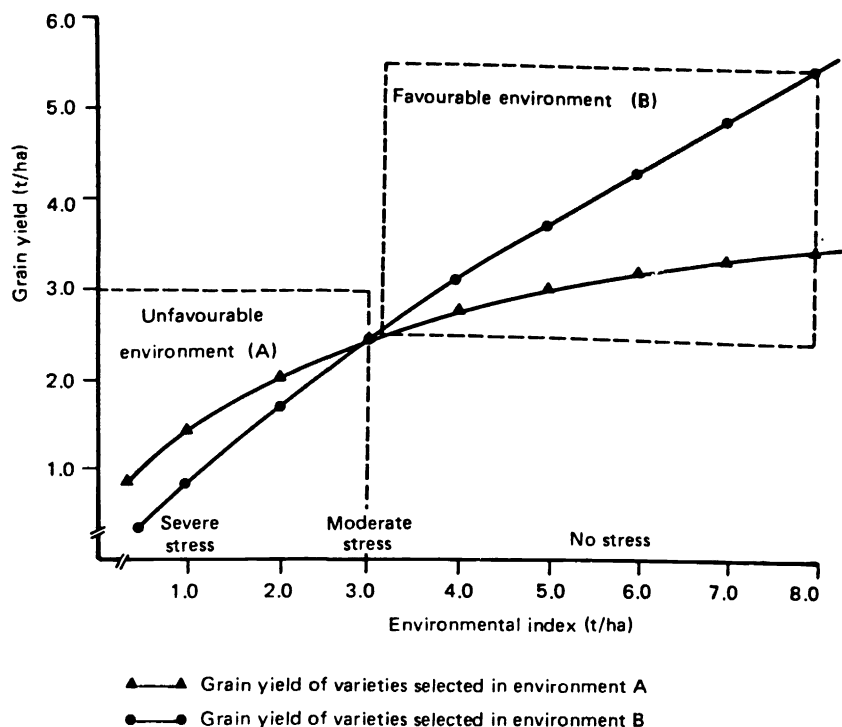


Fig. 7.1. Grain yield of two wheat varieties in (a) unfavourable and (b) favourable crop-growing environments. From Srivastava (1987). By permission of ICARDA and Wiley, New York.

However, stress due to drought, in the semi-arid environments with which we are concerned, is unpredictable in time and in intensity. Specific breeding for drought stress under these conditions will reduce apparent genetic variance and heritability for yield, and limit efficiency and progress in selection for yield under stress (Blum, 1988). Selection under stress will generally result in genotypes of lower yield potential that have relatively low mean yields under non-stress conditions (Rosielle and Hamblin, 1981). Fig. 7.1, from Srivastava (1987), gives a generalized presentation of expected grain yields under different stress conditions: varieties that have been specifically selected in and for a low-rainfall area will produce slightly higher yields than a variety with high yield potential under conditions of severe moisture stress, equal yields under moderate stress, and markedly lower yields in years of adequate rainfall.

Breeding for wide adaptability

In this approach, crop varieties are developed that, on average, produce better than other varieties in a relatively broad range of conditions. The basic premise is that the relative ranking of genotypes for yield potential is similar across environments (Krieg, 1983).

Environments can be vastly different; it should therefore be clear that the concept 'wide adaptability' does not imply adaptability to an unlimited variety of environments; it refers to adaptability to the range of seasonal and locational variability normally encountered in a given eco-geographic area.

It is the misunderstanding of the term 'wide adaptability' that leads to statements such as: "high yielding, widely adapted dwarf wheat varieties of the Pacific Northwest are, in general, not suited to the drought conditions of the Great Plains" (Briggle and Vogel, 1968). Why should varieties suited to a winter-rainfall climate, with relatively high rainfall, be expected to be suitable in a summer-rainfall region under drought conditions? This is widening the term 'wide adaptability' to absurd proportions, and can explain another statement, that "to select for wide adaptability is to select for mediocrity or even low yield" (Reitz, 1975). The HYVs of wheat and rice are evidence to the contrary!

In practice, wide adaptability signifies that in breeding programmes in semi-arid regions, for rain-fed crops, emphasis will be given to traits that enhance the plant's ability to maximize water use, to tolerate intermittent stress and avoid terminal stress; and a genetic yield potential sufficiently high to respond to favourable conditions in seasons of above-average rainfall, in a defined agro-ecological environment.

Successful breeding for wide adaptability

The 'Green Revolution'

It was only after the advent of the so-called miracle varieties of wheat and rice with high yielding ability (HYVs) that the importance of breeding for wide adaptability has become fully appreciated.

The HYVs of wheat, bred at the International Centre for Wheat and Maize (CYMMIT) in Mexico, are successfully grown over a wide range of environments in a worldwide geographic area.

Two generations of segregating materials were grown each year: in a winter nursery at sea level in north-west Mexico at latitude 27°N, and in a summer nursery at 2800 m altitude near Mexico City, at latitude 10°N. Some selections were screened in Colombia at latitude 4°N (Borlaug, 1965).

The original objective of this procedure was to accelerate the breeding programme, by growing two generations every year. It undoubtedly contributed, however, to the wide adaptability of the resultant gene pool of high-yielding lines for final selection. Breeding for insensitivity to photoperiod further extended the range of adaptability of these genotypes. The high-yielding potential of the varieties that were finally released, resulted from an aggregate of characteristics, including resistance to lodging, high ratio grain/stalk, high response to fertilizers, and resistance to many rusts.

Though the range of adaptability of the HYVs of rice bred at the International Institute for Rice Research (IRRI) in the Philippines is less than that of the wheat HYVs, their relatively low photoperiod sensitivity, combined with a gene pool of

diverse origins, conferred adaptability to a fairly wide range of environments to the varieties finally released for production.

The high yields of the IRRI varieties are due to a combination of traits similar to those of the wheat HYVs: resistance to lodging, high ratio grain/stalk, high response to fertilizers, as well as moderate tillering capacity, low responses to variations in temperature, and phenological adaptation.

Whilst the 'Green Revolution' may be one of the most spectacular successes of breeding for wide adaptability, very good results have been achieved in this field, for many crops, both prior to, and after the introduction of the high-yielding dwarf varieties of wheat and rice.

There is considerable evidence that, in general, selection for high yield and wide adaptability has been highly successful in achieving both aims. In addition, it has also resulted in improved resistance to specific environmental stresses, unrecognized at the time of selection (Blum, 1988).

Worldwide, a major effort has been invested in breeding wheat, and the prime goal has been improving yield potential. Breeding for drought resistance has, in the main, been indirect, with the possible exception of adapting crop maturity to seasonal precipitation.

In the US Pacific Northwest, in breeding programmes aimed at increasing yields of winter wheat under semi-arid conditions, significant progress has been achieved. A comparison was made between the average grain yields recorded during the 1931–1952 period, with those obtained during the 1953–1974 period. The results are presented in Table 7.3.

Many of the varieties with high yielding potential under favourable moisture conditions also produced higher yields when moisture was limited (Dryland Agricultural Technical Committee, 1979).

In maize and many other crops, F1 hybrids have shown superior stability across variable environments, as compared to homozygotes. The wider stability of the hybrids is related at least to their relative resistance to a wide range of extreme temperatures and other environmental stresses (Blum, 1988).

TABLE 7.3

Effect of improved varieties and crop management on grain yield of winter wheat in two locations in the Pacific Northwest

Location	Percentage increases in yield (average yields 1931–1952=100) due to:		
	Varieties	Management	Interaction V×M
Lind	17	69	99
Pendleton	32	28	69

Source: based on data from Dryland Agriculture Technical Committee (1979).

Heterosis was found to be associated with greater growth rates and greater total biomass, with or without an apparent increase in leaf photosynthetic rates (Blum, 1988).

Russell (1974), in a comparison of double-cross hybrids of maize in use in the 1930's with modern commercial hybrids, found that the latter performed better at all yield levels, but their relative advantage was considerably greater at the lower-yielding locations where drought stress was a strong limiting factor. The author concluded that screening over the years had added important characteristics needed in stress environments.

In a similar analysis, Duvick (1977) compared 48 maize hybrids according to the years they were released to farmers. The more recent the release, the higher the relative yields at all locations. In contrast to Russell's results, the greatest advantage was recorded at the highest-yielding locations. However, considerable gain had been made even in the most severe drought environments, indicating that traits conferring resistance to stress had been indirectly incorporated in the hybrids over the years, and were useful even in the high-yielding locations, in which intermittent stress at different stages of growth are a normal occurrence.

Finlay (1968) has shown that high-yielding varieties can be selected in optimal environments and could retain their relative superior yield in less favourable environmental conditions. He has presented evidence to show that the two components of adaptation, mean yield over all environments and yield stability, were largely independent of each other. Several genotypes of barley were developed which were able to produce high mean yields over all the test environments. Barley genotypes that had wide adaptation tended to have traits that were intermediate in expression, whereas those with specific adaptation to a particular environment tended to have extreme trait expression.

McVetty and Evans (1980), in selection work with hybrid populations of three wheat crosses in a normal environment and in a stress-free environment (irrigated, fertilized and weed-free) found that the percentages of high-yielding varieties in the two environments were very similar.

Walker and Fehr (1978), working with soybeans in 12 environments, found that they performed relatively the same, irrespective of environment.

Frey (1964) found that the non-stress environment was superior for lines with wide adaptation response and concluded that high production conditions are best for selection and testing in an oat breeding programme.

Roy and Murty (1970), in a study to develop procedures for selecting wheat genotypes with wide adaptation, yet with the response capacity to react positively to stress environments, tested 3 million plants from 533 crosses. Four environments were created: high fertility, irrigated; moderate fertility, irrigated; low fertility, starter irrigation; and low fertility, rainfed. They found that the best selections under stress testing did not derive from a stress environment, but rather from the most favourable environments.

Brennan and Byth (1979) found that the performance of wheat in high-yielding environments was a better predictor of line performance across all environments than was performance in low-yield environments. They concluded that the best selection strategy was to express line mean yield at each environment in percent of environment (site) mean yield, average these across sites, and use these composite figures to select for high relative mean yield.

Though most studies indicate that selection under favourable conditions is more effective in breeding for wide adaptation, occasionally the opposite has been found to be true. Richards (1978), for example, working with rapeseed, found that selection for yield was more efficient under drought conditions than under optimal conditions. He concluded that "the most efficient selection method is the one performed in the environment of expected use".

However, 'environments of expected use' that have drought conditions also have good rainfall years, which may be just as characteristic of the environment as drought years!

Johnson et al. (1968) state that general adaptation is important not just for large areas, but also at times for even a single location because of year $\times$ interaction variances; the lower the average annual precipitation, the greater the variability.

Even when breeding for wide adaptability in drought-prone areas, it must be realized that some compromise between yield potential and adaptability may be inevitable for the sake of stability. This is especially true for less developed countries, where a modest yield in most seasons is more important than very high yields in favourable seasons.

TABLE 7.4

Estimated cumulative yields of three cultivars of wheat grown in a wide range of moisture régimes in an area with adequate average rainfall

Precipitation (mm)	No. of years	Yields (kg/ha)					
		Average			Cumulative		
		Miriam	Bethlehem	V652	Miriam	Bethlehem	V652
200–300	3	3100	2900	2700	9300	8700	8100
301–400	7	3700	3800	3900	25 900	26 800	27 300
401–500	23	4250	4500	4700	97 750	103 500	108 100
501–600	29	4750	5150	5500	137 750	149 350	159 500
601–700	21	5250	5800	6800	110 250	121 800	142 800
> 700	16	5250	5800	6800	84 000	92 800	108 800
Totals	99				467 900	502 750	554 600

Estimations based on data from Blum and Pnuel (1990) and Katzenelson (1985).

An instructive example of the long-range, contrasting response of three wheat cultivars, from among 12 cultivars tested in 16 trials by Blum and Pnuel (1990), with a wide range of precipitation regimes (from 230 to 755 mm) is presented in table 7.4. The three varieties are Miriam, a specifically drought-resistant variety with low adaptability, Bethlehem, a variety with relatively high stability, and V652, with wide adaptability. The variability of rainfall over 99 years is based on meteorological data for an area with adequate average rainfall (450 mm).

In an area with adequate average rainfall, where the expectation for drought seasons is about 1/10, but in which periods of intermittent drought stress may be fairly frequent, breeding for specific drought resistance, or for high stability, appear to be less justified in the long term than breeding for productivity and wide adaptation.

Measuring yield stability

Since the 1960's, several statistical biometric approaches have been developed to identify those genotypes that are stable in their yields over a wide range of environments, and thereby to help the breeder to analyze genetic performance relative to the environment and to categorize varieties in terms of stability.

The earliest, and most widely used, is regression analysis (Finlay and Wilkinson, 1963). The technique involves growing many genotypes in replicate yield trials in a number of sites over a series of years, within the target regions. A judicious choice of sites can substitute for years and thereby shorten the time needed for a testing programme (Jensen, 1988).

The mean yield of all varieties at each site and season (site mean yield) provides a quantitative measure (environmental index) defining site/season combinations as high- or low-yielding environments. A linear regression for the yield of each variety is calculated for each site and season.

The regression coefficient (b) is a measure of phenotypic stability shown by a variety in diverse environments: a variety that shows $b > 1.0$ has less than average stability; conversely, a variety with $b < 1.0$ has higher than average stability.

If drought stress is the main environmental factor affecting variation in the environmental index, genotypic yield responses to this variation can be considered as an expression of drought resistance as expressed by yield (Blum and Pnuel, 1990).

Various improvements to the original regression model have been proposed; a description of these methods and their applicability is beyond the scope of this book, and the reader is referred to the comprehensive review of the subject in Blum (1988).

The direct approach: incorporating desirable physiological and morphological traits for drought resistance into improved genotypes

In recent years, increasing attention has been given to plant characteristics that provide various forms of drought evadence, tolerance or resistance without unacceptable adverse effects on performance. These traits have been discussed in Ch. 6.

The pressure for development of drought resistance is only recently becoming intense, because the alternative, simpler avenues have already been explored (Hanson and Nelson, 1980).

Plant breeders (Blum, 1983; Rosenow et al., 1983) and plant physiologists (Bidinger et al., 1982; Garrity et al., 1982) are working on the assumption that better-adapted and higher-yielding genotypes could be developed more effectively by combining a reasonably high yield potential with suitable plant factors that confer drought resistance and thereby buffer yields against a severe reduction under stress (Blum, 1989).

Barnes (1983) distinguishes between a defensive and an offensive approach to breeding: the defensive approach would be to breed for traits that enable plants to extract more of the available soil moisture without changing the yield per unit water; the offensive approach consists in incorporating traits involving changes in plant anatomy, morphology, and/or physiology which increase the marketable yield per unit of water used.

The first priority in a breeding programme should be to determine what factors are limiting crop yield, considering the unpredictable water supply and random occurrence of stress periods.

Some of these limiting factors could be (Barnes, 1983):

- less than optimum root system, leaf area, and/or vascular system;
- susceptibility to pests and/or diseases;
- unsatisfactory plant establishment.

Major problems in incorporating drought-resistance traits

The physiological approach to breeding for drought resistance requires: (a) an understanding of the physiological parameters of plant–water relations which support plant productivity under moisture deficiency stress; and (b) the availability of tools for the rapid and simple measurement of the relevant attributes in large populations (Blum, 1989).

This approach to the improvement of crops for enhanced performance when submitted to periods of drought stress, poses a considerable challenge. It implies, in addition to using appropriate breeding techniques, an understanding of plant–soil–water relationships and constitutes what is probably the most difficult area of plant improvement research yet attempted (Barnes, 1983).

Most of the previous research has been carried out separately, by plant breeders concerned with genotypic variability, mainly related to yield genes, and plant physiologists studying traits associated with plant–water relations. Considerable achievements have been recorded in both fields, but few of the plant physiology programmes have concerned themselves with applying their findings to actual plant improvement, and demonstrated successes of conscious efforts to enhance drought resistance of crops are still few (Jordan, 1983).

Ludlow and Muchow (1990) also write that there are few examples where this approach has already been applied, and even fewer where it was successful. They ascribe this lack of progress, apart from the objective difficulties involved, to the fact that “too often, traits are advocated based on theory, laboratory experimentation, or correlations (probably more casual than causal) between the presence of the trait and yield in drought-prone environments, without sufficient attempt to demonstrate that the particular trait does contribute to final yield”.

The authors bring, as an example of such an approach, the claims made for proline accumulation as a selection criterium which subsequently was found to be useless for this purpose. Correlations were found between proline accumulation and grain yield in barley in water-limited environments (Stewart and Hanson, 1980). Subsequent research showed that most of the proline was in dead leaves, and hence made no contribution to grain yield, or even to survival.

A further reason for the lack of success in using certain traits for improving crop performance under drought conditions, is that few attempts have been made to establish if there is genetic variability for particular traits among genotypes of the crop, and still fewer attempts to study their inheritance. Ludlow and Muchow (1990) contend that “all these steps are necessary to ensure that a yield increase will occur in the target environment when a trait is introduced into otherwise well-adapted genotypes with good yield potential. With few exceptions, this has rarely been done, and consequently it is not surprising that the success rate has been low”.

Turner (1986) also confirms this view. He writes: “Our understanding of adaptation to water deficits has been significantly improved by crop physiologists and eco-physiologists in the past decade. In particular, new and exciting possibilities exist for the measurement of water use efficiency among crop cultivars. This may lead to the use of a physiological tool for screening for one aspect of drought resistance. However, the possibility of using physiological and biochemical ‘buttons’ that need only to be pressed to improve the drought resistance of a cultivar, has lost most of its credence in the past 10 years”.

Turner concludes that new approaches are required in plant breeding for the incorporation of desirable physiological traits.

Breeding for yield and drought resistance – a two-stage strategy

The major problem confronting the plant breeder who wishes to integrate specific traits for drought resistance, is that, as a rule, decisions have to be made regarding the price in yield that must be paid for the improved ability to tolerate drought.

For example, high yields require a large leaf area, whereas adaptation to drought depends on leaf area adjustment to the available water; rapid shoot growth conflicts with the development of a large root system (Schulze, 1988).

Jordan et al. (1983) have identified only three mechanisms for drought resistance that should not reduce yield: increases in cuticular waxes, in liquid phase conduct-

ance, and in cellular elasticity. Even for these traits it has not been proven that there is no negative effect on yields.

An elegant solution, that avoids this problem, has been proposed by Blum (1983). It is based on the following assumptions:

- That the main difficulty in the current approach to breeding for drought resistance is the use of a genetically complex trait (yield) as a principal selection index, and the use of biologically ‘invisible’ environments for selection towards general stability.
- That the heritability of yield is reduced under conditions in which yield is reduced, and therefore selection for drought resistance by the use of yield as a selection index under drought conditions is inefficient.
- That the large temporal variability inherent in a drought environment makes it difficult to decide what kind of selection environment represents the target environment.
- That improvement of yield under stress must combine a reasonably high yield potential with specific plant traits which would buffer yield against a severe reduction under stress.
- That yield and traits for drought resistance are controlled by different gene systems, and can therefore be selected independently of one another.

From the foregoing, Blum (1989) concludes that “breeding for drought resistance must depart from the use of yield as the exclusive selection index, because of the high cost of this method and the long period of testing and evaluation involved. A direct reference to some physiological attributes in the selection for drought resistance would allow us to address underlying factors of stability”.

In the first stage, selection would address yield potential and general agronomic traits before selection for drought resistance is attempted. Suitable lines are advanced to the F4 generation, by criteria of yield components, disease resistance, lodging, phenology, grain quality, etc.

Most practical selection methods for drought resistance are only appropriate for plant populations, therefore at the F4 stage, any trait that appears desirable even on theoretical grounds alone, should be introduced into the breeding programme, with simultaneous selection for both the trait and high yield. Screening at this stage should be under non-stress conditions. Only *after* the desired trait and yield potential have been combined should the genotypes be further screened in conditions of intermittent water stress.

Future trends

Though progress in the numerous attempts to screen for drought-tolerant characteristics and to incorporate them into suitable genotypes has not yet been substantial

(Schulze, 1988), it is undoubtedly an elegant and logical approach to the problem of breeding crops for rain-fed production under semi-arid conditions. It should be remembered that a similar approach to breeding for disease resistance has been highly successful in many cases (cf. Ch. 19). Several authors stress the need for wide-ranging interdisciplinary teamwork. Further progress "will require the synthesis and integration of many types of information by scientists from several disciplines" (Barnes, 1983). A multidisciplinary approach is needed wherein "elements of micrometeorology, soil physics, crop physiology, agronomy, and plant breeding all contribute to a common solution" (Jordan, 1983). Heichel (1983) also stresses the need for sufficient support personnel and a commitment of adequate resources for several years.

How many countries, in particular the developing countries in the semi-arid areas, can afford such a major enterprise? Apart from the long-term financial resources required, and the uncertainty of success in a relatively new approach to breeding for drought resistance, the scarcity of human resources will be a major obstacle. Even in the developed countries, with adequate numbers of scientists in the many disciplines mentioned above, the personnel will have to be screened for their ability to work as a team; leaders capable of heading such a complex undertaking are also a scarce commodity.

There is one obvious solution. The International Agricultural Research Institutes have amply proven that they are eminently capable of assembling high-level interdisciplinary teams and wide-ranging, comprehensive collections of germ plasm, on a scale few national research organizations can hope to emulate. Close links with all the national research organizations within their sphere of activity can create a framework for cooperative effort at minimal cost to the countries involved, whilst maximizing the probability of success.

Whatever the shortcomings of efforts made hitherto, research on the potential benefits of incorporating specific genetic traits that confer drought resistance in its different forms to improve the performance of cultivars grown in drought-prone environments, will continue to be explored. Hopefully, the research invested in these endeavours will learn from past misconceptions.

Whilst the search for suitable traits that confer drought resistance without requiring a too high cost in performance, will continue, there is no justification for neglecting the conventional breeding methods for yielding ability based on screening large segregating populations under field conditions, in semi-arid environments. In the long run, the most successful genotypes will incorporate favourable traits for drought resistance, mainly in intermittent stress situations. These will be balanced by genetic traits for yielding ability at a level appropriate to the conditions encountered over time in the environment for which the crop is being bred.

Incorporating physiological and morphological traits for high yields*Introduction*

Yield increases of cereals in the last century have been achieved mainly by using grain yield as major criterium for breeding. "... progress through grain yields has depended on combinations of characteristics designated largely by chance, combinations that may be better than those of existing cultivars but which advance toward any ideal combination only by a wandering path with many blind byways" (Donald and Hamblin, 1976). Progress in other crops has been along similar lines. Despite the success of this pragmatic approach it has, according to these authors, two limitations:

- it is unlikely to achieve radical combinations of plant characteristics able to give dramatic yield increases above those already achieved;
- it is an uncertain and sometimes misleading criterion for early generation selection, so that superior genotypes may remain unrecognized.

Good and Bell (1980) write that "Breeding for the end result of interactions of a multiplicity of unknown gene-controlled processes is inevitably a matter of unsystematic and very time-consuming trial and error". The authors conclude that "identification of the components of yield in terms of specific physiological processes should take much of the randomness out of breeding. ... only to the extent that we can describe productivity in terms of the mechanisms that control photosynthesis and growth can we bring productivity improvement out of the dark ages of pure empiricism".

Blum (1990) comes to a similar conclusion, stating that yield improvement by raising the genetic yield potential does not constitute a durable solution if one accepts that potential yield is close to being achieved or very difficult to improve by traditional methods.

Nor is direct breeding for yield per se a viable alternative: there are no genes for yield per se, and therefore there can be no heritability of yield. "It is the multitude of physiological and biochemical processes at any level of organization that are under genetic control, when the total is integrated toward an effect on yield" (Blum, 1988). Blum and Pnuel (1990) further point out that genetically, yield is characterized by low heritability; there are large variations in yield due to environmental factors, in particular in drought-affected areas, with low yield potential.

The planned maximum accumulation of genes for productivity into a single genotype, capable of transmitting this complex intact to its progenies, is therefore not feasible at the present stage of our knowledge.

Consequently, "it is preferable to use a specific physiological attribute as a selection index rather than the genetically labile and complex trait defined as yield" (Blum, 1988).

Many research workers have adopted this view, and considerable efforts have been

invested in research on physiological and morphological traits (apart from those specifically concerned with drought resistance, discussed in the previous section) that might contribute to raising yields above the presently achieved levels. Incidentally, it should be pointed out that many of these traits are also relevant for crops grown in drought-prone environments, in particular for the first stage of Blum's two-stage strategy.

It is only natural that this approach also has limitations and entails certain risks. Rasmusson and Gengenbach (1983) stress the risk involved in shifting resources from existing successful breeding programmes to programmes for incorporating physiological traits, where success is still less certain. To this, Evans (1975) adds: "Knowledge of the direct effects of breeding for specific physiological traits is still fragmentary, and much of the available information has been obtained from inference from experiments or breeding programmes designed to answer more general questions".

In the discussion on breeding for high yields in drought-prone environments (cf. p. 276), it was pointed out that a trade-off between yield and drought resistance was necessary. No such restriction exists for more favourable environments, such as irrigated agriculture.

Apart from this distinction, the breeder faces the same dilemma of whether to breed for specific ecological niches or for wide adaptability, and the conclusions reached in the context of the genetic approach to breeding for drought resistance are also valid in the present context.

One of the principal tools of the plant breeder has always been the choice of appropriate parents for crossing programmes, in which the objective is to breed new genotypes, combining the favourable characters of the parents. A severe limitation of this method has been the lack of knowledge of the physiological process on which crop productivity depends, making the choice of parents a haphazard process (Boonstra, 1934).

Wilson (1983) stipulates that it should be possible to increase biological yield by:

- increasing photosynthetic capacity of the single leaf;
- improving light interception characteristics of the crop;
- reducing wasteful respiration.

The physiological basis of yield

Most seed plants have three rather distinct growth and development phases (Krieg, 1983):

(a) Development of leaf area and vegetative tissues; during which most photosynthates are used to make more photosynthetically active plant material. At first, rapid growth is necessary to make efficient use of water and nutrients whilst they are relatively abundant and to be able to compete with neighbouring plants;

(b) Attainment of maximum leaf area, maximum rates of dry matter accumula-

tion and development of the potential yield container, during which the major effort is directed at producing materials that will be stored in the yield-producing organ;

(c) The *reproductive stage*, e.g. the growth of reproductive organs that will use the already existing vegetative plant.

Yield is therefore the “culmination of a sequence of stages of plant development, all of which are subject to genetic control, presumably mediated by hormones and by as yet unidentified agents of differentiation” (Good and Bell, 1980), and all of which are ultimately dependent on a unique biochemical process – photosynthesis.

The first prerequisite for high yields is a high production of total dry matter per unit area.

Carbon compounds account for 80–90% of the total dry matter produced by plants. Photosynthesis is the basic process for the building of organic substances by the plant, whereby sunlight provides the energy required for reducing carbon dioxide, with sugar as the endproduct of the process. This sugar serves as ‘building material’ for all the other organic components of the plant.

The amounts of dry matter produced will therefore depend on the effectiveness of photosynthesis of the crop and, furthermore, on plants whose vital activities are functioning efficiently.

Breeding for increased yield must, perforce, relate to increasing efficiency in capturing and transforming solar energy. The relationship between photosynthesis and crop yield is, however, complex, and plant breeding research has not generally been directed specifically at improving the photosynthetic process (Wittwer, 1980).

The principal means for enhancing photosynthesis that will be discussed here include:

- (a) optimizing the assimilating area (leaf area and duration) and improving the interception of photosynthetic active radiation (PAR) (plant architecture);
- (b) improving efficiency of the photosynthetic process, by improving net assimilation rate (NAR) and reducing photorespiration; promoting a high initial growth rate;
- (c) redistribution of photosynthates in order to maximize economic yield.

Interception of solar radiation by crop canopy

The effectiveness of photosynthesis is dependent on (1) a large and efficient assimilating area, (2) an adequate supply of solar energy and carbon dioxide, and (3) favourable environmental conditions. If we assume that, under irrigation, in an arid climate, (2) and (3) will not be limiting, the total products of photosynthesis throughout the lifetime of the crop will depend on the size of the assimilating area, the efficiency with which it functions, and the length of the period during which it is active.

There is, accordingly, full justification in assuming that differences in productivity

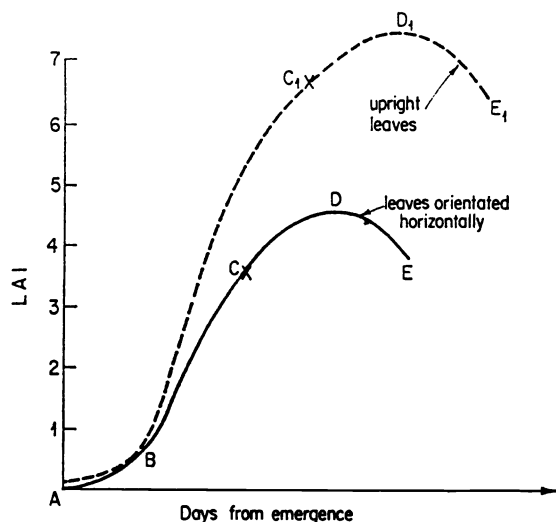


Fig. 7.2. Schematic presentation of growth curves of leaf area index (LAI) for two plant types with upright and horizontally oriented leaves, respectively. AB=period after emergence; BC and BC_1 =period of rapid growth; C and C_1 =optimum LAI, when lower leaves are at compensation point; D and D_1 =maximum leaf area.

between cultivars will depend to a large extent on inheritable characteristics of the structure and function of the organs involved in photosynthesis (Stoy, 1963).

Leaf area index. The leaves of a plant are normally its main organs of photosynthesis, and the total area of leaves per unit area of land surface, called leaf area index (LAI), has therefore been proposed by Watson (1958) as the best measure of the capacity of a crop for producing dry matter; this he calls its productive capital.

Variation in total leaf area (LA) of a plant may result from changes in leaf number or in leaf size. The number of leaves present at any particular time equals the total number of leaves produced minus the number of leaves that have been lost by abscission. Leaf number depends on the number of growing points, the length of time during which leaves are produced, the rate of leaf production during this period, and the length of life of the leaves. Leaf size is determined by the number and size of the cells of which the leaf is built, and is influenced by light, moisture régime, and the supply of nutrients.

Growth curve of LAI (Fig. 7.2). After germination, LAI increases very slowly at first, over a fairly long period; then follows a period of rapid expansion. As LAI increases, light interception and the rate of dry-matter production increases, until the foliage becomes sufficiently dense to cause mutual shading. Then less light penetrates to the lower leaves, whose photosynthetic activity is therefore reduced.

In the early literature on LAI (Watson, 1956), it was assumed that crop growth rate was proportional to the fraction of incoming radiation intercepted by the canopy, and reached a ceiling when full interception was achieved. It was found that a LAI of at least three was necessary to intercept 90–95% of the incoming radiation. At higher LAI values, the shaded leaves, which respire as actively as those receiving full sunlight, would become sinks rather than contribute to photosynthate production. The conclusion reached was that there is an optimum LAI (LAI_{opt}), for maximum dry-matter production, which is reached when the lowest leaves receive just sufficient light for photosynthesis to balance respiration – e.g., when the lower leaves are at the compensation point, and the canopy as a whole has reached maximum net assimilation. Below optimum LAI, light energy is not being fully intercepted; above optimum LAI, the leaf area is not being utilized at maximum efficiency.

It was subsequently found that there was little evidence to support the assumption that shaded leaves were important respiratory sinks for current assimilates, and it is now generally assumed that overall rates of respiration of crop canopies are more closely related to the rate of gross photosynthesis than to biomass or leaf area (Hay and Walker, 1989).

Consequently, it is now accepted that for most crops the growth rate increases up to a critical value of LAI at which interception is complete (LAI_{crit}), usually for values of three to five, and even higher for crops with leaf angles greater than 60° to the horizontal, above which a relatively constant and maximal growth rate is maintained (Hay and Walker, 1989).

Differences in LAI_{crit} depend on the light intensity (being higher under high light intensity up to saturation) and on the manner in which light is intercepted by the crop canopy. This latter factor varies with crop species, and even between varieties of the same species. The light received by a crop with a large optimal LAI is spread over more leaf surface than is the case with a crop having a low value for optimal LAI; this results in a lower intensity of illumination for most leaves, at which photosynthetic efficiency is higher than with more intense illumination (Watson, 1967).

Importance of high initial rate of growth. For most annual, closely spaced crops, LAI is lower than optimum during most of the growing period. So long as $LAI < 1$, some of the incident solar energy is not intercepted by leaves, and reaches the soil. Turner and Nicolas (1987) postulate that in a winter-rainfall zone, wheat plants with early vigour maximize water use and minimize water loss during the winter months when moisture is plentiful, and that vigorous early growth resulting in high dry-matter yields before anthesis result in improved grain yields.

During the young seedling stage, photosynthesis and crop growth rate are limited by the low ability of the crop to intercept light. At this stage, there is little shading, most of the leaves are photosynthesizing at or above the light saturation level, and NAR is high (Wilson, 1983).

In a crop grown from seed, it might be possible to shorten the period of very low

LAI by breeding cultivars with a high initial rate of growth, especially under irrigation, which provides favourable conditions for rapid growth (Stoy, 1963).

Leaf area duration. The yield of dry matter can be derived from the following formula:

$$Y = LA \times NAR \times t,$$

in which Y = total production of dry matter, LA = assimilating area, NAR = net assimilation rate, and t = time.

The length of the vegetative period (t) is obviously of great importance in determining the effect of LAI on yields. Crop improvement aimed at the most efficient use of the available growing season may contribute considerably to increased productivity. An integral of LAI over the growth period is a measure of the combined action of LAI and time, and is called 'leaf area duration' (LAD) by the English workers and 'photosynthetic potential' by the Russians. LAD is a measure of the opportunity for assimilation throughout the life of the plant.

Of all the parameters of the photosynthetic apparatus (size, LAI, and leaf area duration), it is the leaf area duration (LAD) that has the highest positive correlation with grain yield (Loomis and Williams, 1963). It is one of the traits that characterizes the newer and higher-yielding maize hybrids, as compared to those grown in the 1930's (Cavalieri and Smith, 1985).

There are genetic differences in LAD between cultivars; this parameter is also affected by environmental factors at the time of its development as well as by plant diseases (Borojevic, 1990).

It must, however, be stressed that the rapid increase of LAI, and its maintenance over a long period, create at the same time a transpiration mechanism that favours the loss of huge amounts of water which are needed to dissipate the enormous amounts of energy absorbed. This is of particular importance in arid-zone agriculture, and is a reminder of the close relationship between efficient photosynthesis and water regime.

Effects of moisture stress. Depending on the time and duration of moisture stress, crop yields will suffer from a reduced LAD, due to delayed canopy growth, lowered peak LAI, premature leaf senescence, and possibly a combination of these effects (Hay and Walker, 1989).

Leaf age. In many species, a progressive decline in NAR with leaf age after maturity has been recorded. The age at which this decline begins varies between species and within species. Whilst the photosynthetic activity is considerably reduced, respiration continues as long as the leaves remain alive.

It is possible that selection criteria for reduced leaf senescence could be developed (Wilson, 1983).

Blum et al. (1983b) point out that post-flowering leaf senescence under the effect of drought stress is not necessarily a negative drought response. In cereals, at this stage, 30 to 40% of the plant's production of photosynthates are contributed by the ear; carbon assimilation by the leaves is already at a very low level and stem reserves are an important source for grain growth under stress. Therefore, leaf senescence under stress at this stage reduces transpiration losses, and may even be a drought adaptation response.

Genetic response to light intensity. There are marked differences between different species in their response to light intensity. Single leaves of some plants, such as tobacco, are saturated at near one-quarter of sunlight, whilst other crops, such as maize, sunflowers, and sugar cane respond to differences near to full sunlight.

There are also major differences in the maximum rate of photosynthesis ($P_{\max}$) between species with different photosynthetic pathways. Most C3 crops appear to saturate at about one-quarter of full sunlight, whilst C4 crops respond up to near full sunlight, provided CO_2 is not limiting (Wilson, 1983).

The leaves of most crops are known to be reasonably efficient at low light intensities: the less light received by an individual leaf, the more efficiently it will be used. A shaded leaf may achieve a conversion efficiency of up to 20%, whilst a light-saturated leaf will usually convert into assimilates no more than 1% of the absorbed energy (Gaastra, 1959). A breeding objective could be to increase light conversion efficiency at higher light intensities, either by raising the level of light saturation or by reducing light absorption above the saturation.

Summing up. Of all the parameters of the photosynthetic apparatus discussed above LAD has shown the greatest positive correlation with grain yield (Loomis and Williams, 1963) and increases in total dry-matter production have nearly always been achieved through larger and longer-lasting leaf canopies, rather than by increasing photosynthetic efficiency per unit leaf area (Gifford et al., 1984). Nevertheless, LAD has not been used as a breeding criterion; the actual measurement of LAD, even when limited to the flag leaf, is impractical because it requires more work than measuring yield itself (Borojevic, 1990).

The proportion of incident light that is intercepted by the canopy does not depend on LAI alone, but also on the so-called 'architecture of the plant community' (Loomis et al., 1967).

Fitter and Hay (1987) state that "in terms of plant-breeding it seems that much more can be obtained by alterations in canopy architecture than in photosynthetic rates, which Sheehy and Cooper (1973) found to be unrelated to growth rate".

Effect of canopy structure on light interception. The maximization of light interception by a crop is a major objective of agricultural management practices (Fitter and

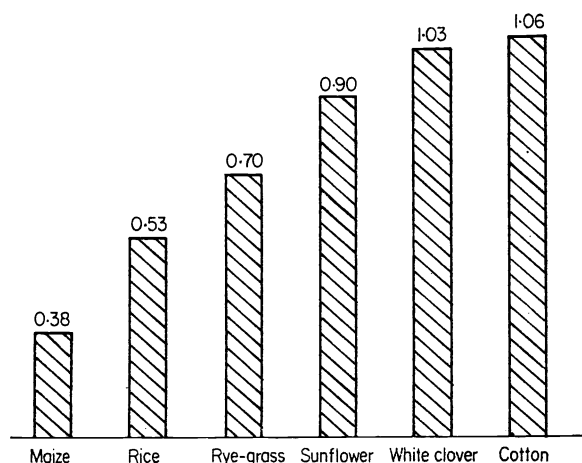


Fig. 7.3. Extinction coefficient (K) for a number of crops. Based on data from Warren-Wilson (1969).

Hay, 1987). In a crop, leaves are not isolated but are arranged in a canopy. The way they are arranged will affect the proportion of incident light that is intercepted by the crop canopy as a whole.

Variations in canopy structure affect the crop in two ways: through light interception and distribution; and through correlated physiological, developmental, and morphological changes (Evans, 1975).

The extinction coefficient. The extinction coefficient (K) is a measure of the light-intercepting efficiency of the leaf area (Warren-Wilson, 1969). Leaf characters of importance in this respect are: leaf angle, leaf area, continuity of leaf layers, and randomness of dispersion of leaves (Donald, 1961).

Interrelationship between LAI and K . Under conditions of limited moisture supply which can support only a relatively low plant population per unit area, the LAI optimum is low and a high K is therefore advantageous in maximizing interception. By contrast, when moisture is not limiting, a low K becomes beneficial because it enables optimum LAI to be high. Under these conditions, photosynthetic efficiency of light utilization is optimal: at high LAI, a lower K ensures that the total light available is dispersed over a greater area of leaves, but the light is proportionally weaker. Photosynthetic efficiency of light utilization being greatest in weak light, this is a manifest advantage in improving dry-matter production.

To achieve the maximum rate of photosynthesis of the canopy per unit ground area, light flux density should be as high as possible, K should be low, while the optimum value of LAI depends both on light intensity and on K (Warren-Wilson, 1969).

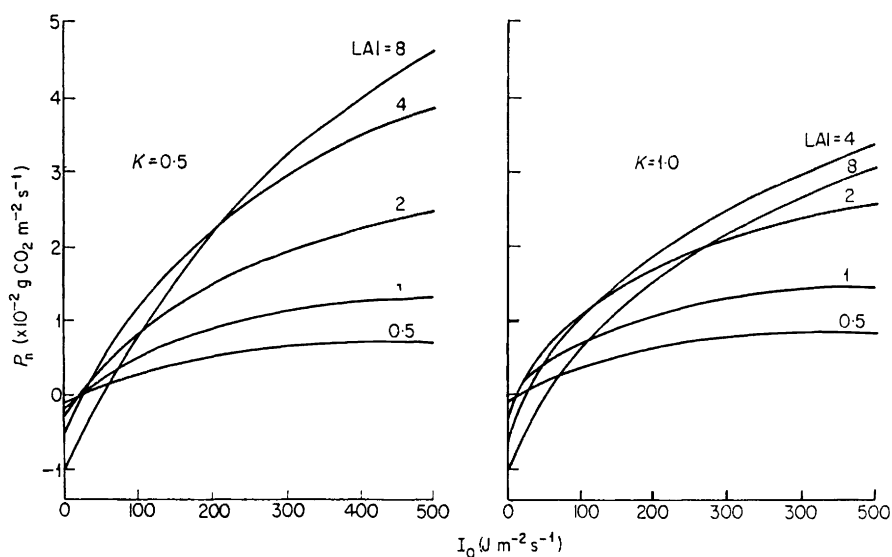


Fig. 7.4. Effect of leaf area index (LAI) and light flux density (I_0) on net photosynthetic rate per unit ground area (P_n) for leaf canopies with extinction coefficient $K=0.5$ (left) or 1.0 (right), respectively ($J=\text{Joule}$). From Warren-Wilson (1969). By permission of the International Potash Institute, Berne.

All these characteristics influencing K are controlled genetically, and could serve as a basis for breeding with the aim of increasing the optimum level of LAI. It has been stated that the high productivity of modern varieties of sugar beet, as compared with the ancestral wild beet, is due to a different disposition of the leaves. Instead of the rosette of the ancestral type, the upright leaves of the cultivated varieties enable a more efficient use of light (Watson, 1956).

In a study of factors that are characteristic of high-yielding rice varieties, it was found that they have erect, short, narrow, thick, dark-green leaves and thick, sturdy stems. The thick, dark-green leaves lose less light through reflection than do others. The narrow leaves and erect positioning permit uniform light distribution throughout the canopy. However, as leaf area is small, these varieties produce heavy yields only if they are supplied with adequate amounts of nitrogen, and if the plant population density is high (Jennings, 1964).

An understanding of plant characteristics which are related to efficient utilization of light can therefore serve as a guideline for defining model plants for selection and breeding work (Figs. 7.3 and 7.4).

Leaf angle (Fig. 7.5). Warren-Wilson (1969) suggested that erect leaves have an architectural advantage. At an inclination of 80° from the horizontal, the intensity of the light received by a plant canopy is optimal and it is spread over a greater leaf area (Duncan et al., 1967).

In terms of leaf posture, a low value of K (0.3) indicates mainly erect leaves,



Fig. 7.5. Two wheat cultivars with sharply contrasting leaf angles. By courtesy of C.M. Donald, Waite Agricultural Research Institute, Australia.

whereas a high value (0.9) relates to nearly horizontal leaves (Monteith, 1965).

The potential benefits of erect leaves have been quantified in models (Monteith, 1965) which predict that for an LAI of 4–5, the maximum difference in photosynthesis to be expected between canopies with erect and those with horizontal leaves would be about 10–15%. Angus et al. (1972) have shown that at this LAI, the reason that erect leaves of barley resulted in increased yields was because the crop was able to respond to increased plant populations.

Leaf angle has a smaller influence on canopy photosynthesis in C4 species than in C3 species (Evans and Wardlaw, 1976). The former are of predominantly tropical or subtropical origin and have evolved under conditions of high irradiance, and are therefore less prone to reach light saturation. Therefore the efficiency of photosynthesis of the individual leaf is reduced only at very high radiance (Hay and Walker, 1989).

Notwithstanding the potential benefits of erect leaves, breeding for this trait has not always been successful, as illustrated by the following examples.

Because individual plants of C4 cereals are much larger than those of C3 cereals, and have larger leaves and greater vertical separation between them, plants are more distantly spaced in the field. Therefore, the advantage of having horizontally inclined leaves in the early stages of crop growth is greater than in the dense stands of C3 cereals. Similarly, erect leaves in cultivars bred for sparser communities, as in the drier areas, for example, would be of less importance (Evans and Wardlaw, 1976).

There may be other reasons for the lack of positive effects of erect leaves, such as a negative influence on other plant functions. For example, if weeds are not controlled chemically, erect leaves lose their potential advantage, because of the inability of the crop to compete with weeds.

Wilson (1983) stresses that the most appropriate leaf design for high economic yields depends on the crop and on whether grain or forage is the economic product. He cites as an example of contrasting responses the short, thick, erect leaf with high $P_{\max}$ considered most suitable for the rice plant and for sugar cane compared with the long-leaved leaf with relatively low $P_{\max}$ resulting from selection for high grain yield in wheat.

Borojevic (1990) states that leaves with a curved position and angles of about 30° between the stem and the ascending part of the leaf are preferable to erect leaves; on screening a wheat collection of 1400 entries from 36 countries, it was found that at the heading stage about 70% of the entries showed curved flag leaves, and only 15% had erect leaves. He concludes that the process of selection had favoured the curved type of leaf.

Other leaf characteristics, besides leaf angle, affect the amount of PAR absorbed by the plant canopy: leaf surface properties that affect reflectance (cf. p. 237); leaf thickness (influences transmission); leaf size, shape, degree of dissection, as well as phyllotaxis and vertical stratification of LA, which govern direct penetration of radiation (Hay and Walker, 1989).

Management practices for optimizing leaf area. Complete control of leaf area for maximizing NAR is not feasible, but it is possible to optimize LA. One possibility is to increase the interception of photosynthetic active radiation by the canopy throughout the growing season, and to improve the distribution of PAR among the leaves by modifying plant architecture (Hay and Walker, 1989). Management practices, such as plant population density, row width and orientation, date of seeding, fertilization, and irrigation, can also contribute to optimizing leaf area.

Photosynthetic efficiency

Maximum potential dry matter production. Penman (1968) calculated a theoretical efficiency of conversion of total radiant energy of about 8% (Fig. 7.6). This figure should be compared with those obtained in actual farming practice: 0.03 in India and 0.36 in Europe.

Based on certain theoretical and empirical considerations, McKey (1980) has cal-

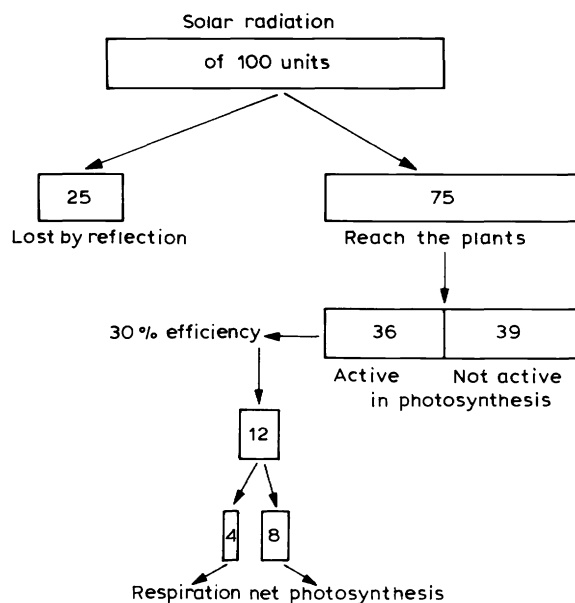


Fig. 7.6. Theoretical efficiency of conversion of total radiant energy. Based on data from Penman, 1968.

culated that the potential net production of biomass by a crop is 670 kg/(ha day), under ideal growing conditions. For a cereal crop, with a growing period of 100 days, and a ratio of grain : straw : root of 5 : 3 : 2, the potential yield of grain (at 12% moisture) would be 67 000 kg/ha (Borojevic, 1990).

Short-term yields of dry matter, at periods of top growth and under controlled conditions, have been obtained that are very near to the theoretical maximum. C4 crop species, such as maize, have produced 60 g/(m² day), and even a C3 crop, rice, produced 55 g/(m² day). These figures indicate that there are cultivars with very high genetic yield potentials (Borojevic, 1990). Photosynthetic efficiency throughout the growing season will inevitably be less than that recorded for short periods, because of periods of incomplete interception of radiation, and the reduced ability of plants to make full use of PAR during periods when they are subjected to environmental stresses (Hay and Walker, 1989).

Of more practical interest are record yields obtained in the field, when all inputs have been optimized, and the capture of light is the overall limiting factor. Though these yields are only half or less the theoretical potential, they are still 2 to 7 times higher than the average yields of the same crops, year and country.

The foregoing does not imply that the achievement of maximum possible yields is a desirable objective in commercial farming. The law of diminishing returns is operative in respect of all inputs, and maximum yields are generally not justifiable economically.

Carbon balance. A proportion of the photosynthates will be needed for the vital processes of the plant, and consumed – by respiration – by the plant itself. The total yield of dry matter will therefore be the total amount of dry matter produced minus the photosynthates used for respiration, e.g., the *net photosynthesis*.

Net assimilation rate. The rate of net photosynthesis can be expressed as

$$P_n = P_g - (PR + R),$$

in which P_n is net photosynthesis, P_g is gross photosynthesis, PR is photorespiration, and R is 'dark' respiration.

Net photosynthesis, or dry-matter production, is the balance between the process of CO₂ fixation and CO₂ release by the plants. These processes determine the efficiency with which intercepted PAR is used for the conversion of CO₂ into crop dry matter (Hay and Walker, 1989).

When net photosynthesis is expressed per unit leaf area, it is called the 'net assimilation rate' (NAR), and can be calculated by the following formula:

$$NAR = \frac{\text{increment in dry weight}}{\text{mean leaf area} \times \text{days}} \quad [\text{in g}/(\text{m}^2 \text{ day})].$$

Respiration rates and components. The net assimilation rate (NAR) does not merely reflect photosynthetic rates but is also influenced by respiration rates. The proportion of the photosynthates used for respiration varies widely with the crop and the environment and is generally quite substantial. However, not all the dry matter used for respiration can be considered as wasted. Warren-Wilson (1969) distinguishes between three components of total respiration:

(a) *Constructive respiration.* Respiratory energy is required for the synthetic processes on which structural growth depends. A close relationship has been shown to exist between relative growth-rate and respiration rate in a number of crop plants, indicating that, for each gram of tissue synthesized, about half a gram of substrate is respired to provide energy.

(b) *Maintenance respiration.* In addition to providing energy for growth, respiration is necessary to maintain the existing organization, such as maintaining the concentration of mineral salts in the tissues.

(c) *Substrate-induced respiration.* Respiration also occurs that is not related to productive metabolic processes. For example, respiration is known to increase when the level of sugars in the tissues exceeds a certain level.

Photorespiration. The rate of oxidation of photosynthetic products by photorespiration is about five times the rate of respiration in the dark. Photorespiration appears to confer little or no benefit on the plant.

Crop species using the C4 pathway for carbon fixation are far more efficient than C3 crops; most of the lower efficiency of the C3 species is due to greater

phosphorespiratory losses. For example, a typical C3 grass, *Festuca elatior*, lost about 40% of its assimilates by photorespiration, whilst a typical C4 grass, *Panicum maximum*, lost only 3% (Brown, 1978).

Respiration rates also depend on temperature and are more temperature-dependent than photosynthesis. In lucerne, for example, Stanhill (1962) found that over the temperature range of 9°C to 26°C, the positive effect of temperature in increasing the rate of photosynthesis was about 20% of the negative effect caused by increasing the respiration rate. Photorespiration is also more stimulated by increases in temperature than dark respiration (Zelitch, 1971).

Dark respiration. Because plant respiration continues when there is no light for photosynthesis, it has been called 'dark' respiration. It is now widely held that 'dark' respiration is a misnomer, as it continues in the light, although at a somewhat different rate, simultaneously with photosynthesis and photorespiration (Graham, 1980).

The losses of photosynthates due to dark respiration cannot be eliminated because the process is involved in normal plant functions, but a reduction might improve productivity. Heichel (1971) compared two maize hybrids: one had a 50% faster growth rate than the other, which the author related to the slower dark respiration in the leaves of the more efficient hybrid.

Relationship between NAR and LAI. Various experiments suggest that NAR is almost independent of LAI when the latter does not exceed three, but decreases when LAI increases beyond this point. If NAR decreases with increases of LAI beyond a certain range, crop growth rate cannot be linearly related to LAI, but must increase more and more slowly with increasing LAI, eventually reaching a maximum, and subsequently falling (Watson, 1967).

Factors affecting NAR. NAR varies between and within species, and is influenced by mineral nutrition, water supply, and seasonal climatic conditions. The variation between years for a given species grown at the same site, and between varieties in the same year, is, however, much greater for leaf area (LA) than for NAR.

Similarly, agronomic practices, such as the rate of supply of nutrients, affect dry-matter yields mainly by their influence on leaf growth, whilst variations of NAR are usually of minor importance and show no consistent trend (Watson, 1956). In general, it can therefore be stated that increases of dry-matter yield depend much more on higher LA than on NAR (Heath and Gregory, 1938).

From these observations it has been concluded that there is little prospect of increasing yields through increasing NAR by breeding or by special treatments. Yet not all authors are convinced that differences in NAR between varieties have little selection value. Even small increases in the rate of photosynthesis can result in fairly big increases in dry-matter production, because the latter accumulates according to the principle of compound interest. Wallace and Munger (1966) found that the high

relative growth rate and large biological yield of one of their bean varieties was due, at least in part, to a 25% advantage in NAR.

Sugar beet (*Beta vulgaris*) and spinach (*Spinacia oleracea*) are closely related and have very similar LA values and leaf arrangements. Yet the NAR of sugar beets is always higher than that of spinach, by an average of 56% (Thorne, 1966), and the dry-matter accumulation of sugar beets is much greater than that of spinach – presumably because the root of the sugar beet provides a more efficient ‘sink’ for carbohydrate than does that of spinach.

Some of the factors that influence growth affect LA and NAR in the same direction; these include increases in N and water supply. Others, such as light, may have opposite effects, and the resultant variation in dry-matter production will then tend to be small (Watson, 1952).

Water supply (irrigation), in particular, has a considerable effect on NAR. A severe moisture deficit normally reduces the rate of photosynthesis considerably – directly through changes in plasmatic structure, and indirectly through closure of the stomata (Stoy, 1963). It is therefore probable that part of the increase in yield that is due to irrigation is attributable to an increase in NAR.

If NAR cannot be markedly increased by most cultural treatments, efficiency in dry-matter production can be improved by making maximum use of the period during which climate favours high NAR, and this may be an important reason for differences in efficiency between species, cultivars, sowing dates, etc. (Watson, 1956). It might also be possible, by breeding, to improve the absorption of CO₂ by the plant and also its transport to the sites of photosynthetic activity (Stoy, 1963).

Photosynthetic efficiency and yield. The direct cause and effect relationship between photosynthetic efficiency and yield is difficult to establish (Moss and Musgrave, 1971). Deficiencies in water supply, nutrition, climatic factors, management practices and many other factors can obscure the effects of photosynthesis. It is however clear that no increase in yield is possible at low photosynthetic rates.

The best measure of photosynthetic efficiency is the total productivity over the whole growing season. On the whole, such productivity can be attributed to the cumulative interception of PAR, rather than to any influence of NAR. In comparisons within and between genotypes, NAR did not correlate well with crop yield, and a review of breeding efforts suggests that NAR has been unimportant in past improvements in yield (Hay and Walker, 1989). Modern bread wheat, for example, has a lower NAR than some of its progenitors (Evans and Dunstone, 1970). The increased grain yields have been accompanied by increased leaf area. As there is a negative correlation between leaf area and NAR, it is possible that the comparatively low NAR of bread wheat is the inevitable consequence of breeding for high yield (Hay and Walker, 1989). There is however a continued interest in the reasons for variation in NAR among genotypes, and in the possibility of breeding genotypes with high NAR (Hay and Walker, 1989).

The main aspect of respiration that is of concern to breeders is to improve crop energetic efficiency by reducing energy losses through photorespiration. Zelitch (1975) estimated that the elimination of wasteful photorespiration in at least a number of crops could increase yields considerably, if it would be possible to incorporate the desirable enzyme system responsible for the C4 pathway. He cites a possible increase of 50% for crops such as wheat and soybeans.

The realization that the elimination of photorespiration in C3 plants could allow increases of net photosynthesis of up to 50% has prompted much research aimed at reducing photorespiration, genetically or chemically. In the 1970's there was much optimism that breeding could produce C3 plants with low rates of photorespiration (Hay and Walker, 1989). These authors stress that "due regard should be given to the wisdom of attempting to banish an apparently wasteful process which nonetheless has persisted in the face of natural selection".

This view is confirmed by biochemical experiments that suggest that energy dissipation by photorespiration protects the photosynthetic apparatus from damage from photo-oxidative processes during periods of CO₂ shortage, such as might be caused by stomatal closure at high light intensities (Krause et al., 1978).

Extensive screening programmes in wheat, barley, oat, soybean, and potato have failed to find genotypes with low CO₂ compensation points (Hay and Walker, 1989).

In a comprehensive review of cultivar differences in photosynthetic rate, Evans and Wardlaw (1976) conclude that there is no clear evidence among cereals of any increase in photosynthetic rate in the course of their improvement in yield ability. The authors consider this finding surprising in view of the central role of photosynthesis in relation to crop growth and yield, and attempt to explain this apparent paradox by the possibility that some counterproductive feature may be associated with further increases in photosynthetic rate.

However, in view of the lack of a simple, satisfactory method of measuring photorespiration, and the many uncertainties involved, "there seems little point in breeders attempting to breed for low apparent photorespiration at present" (Evans, 1983).

As to the greater photosynthetic rates in C4 plants, associated with their reduced photorespiratory losses, Evans and Wardlaw (1976) point out that this may be an advantage at high light intensities, but that in overcast weather, or for leaves deep in the canopy, their photosynthetic rate may be less than that of C3 plants.

Dry-matter partitioning

Biological and economic yields

We have discussed at length the ability of the plant to produce a high yield of carbohydrates. In certain crops, such as those produced for forage, the total dry-matter production or biomass has economic significance; however, this is not the case with most cultivated crops. Generally, only part of the crop is important to the farmer, the rest being either of inferior value (such as in the case of straw of cereals), or a

nuisance to be disposed of, as in the case of the stalks of cotton or the haulms of potatoes). It is the part of the biomass that is converted into the economic product that is called 'economic yield' (Y_{econ}).

Harvest index

The relationship of the economic yield to the total, or biological yield, is expressed as the *harvest index* (HI), which has been defined as "the ratio of economic yield to shoot biomass at maturity" (Ludlow and Muchow, 1990), according to the equation:

$$Y_{\text{biol}} \times \text{HI} = Y_{\text{econ}}$$

There exist, therefore, two different, though not necessarily antagonistic, pathways that can be followed in breeding for high yields. These are:

- (a) increasing the total production of dry matter (Y_{biol}), which has already been dealt with, and
- (b) increasing the proportion of the total dry matter produced that is accumulated in the parts of the plant which are of economic importance (Y_{econ}), i.e. by increasing the harvest index (HI).

A balance between the productive parts of the plant and the reserves which form the economic yield is essential. Experience has shown that a considerable increase in the yield of the economic product is usually dependent on an increase in the total dry matter produced. However, this is not an absolute relationship; indeed, in extreme cases, the opposite may be true. In maize, high plant populations, which produce the greatest biomass (and are therefore the most efficient in utilizing radiant energy), may produce little or no grain because of excessive competition between the plants for light.

Factors affecting the harvest index

HI and biological yield. Harvest index depends, inter alia, on the relative proportion of pre- and post-anthesis biomass and on the remobilization of pre-anthesis assimilate to the grain (Ludlow and Muchow, 1990).

In many cereals, most of the dry matter in the grain is produced by photosynthesis after the ears emerge. Grain yield therefore depends to a large extent on the photosynthetic activity of the parts of the plant that are still green after anthesis. In wheat, barley, and similar cereals, the photosynthetic activity of the ear, which is situated at the top of the stalk, makes a considerable contribution to grain formation. Practically all the dry matter of the grain is produced by the part of the shoot above the flag-leaf node. In wheat, 61 to 83% of the variation in grain yield could be predicted from the duration of photosynthesis of the flag leaf and sheath (Spiertz et al., 1971). The rest is translocated from stored stem reserves.

Similar results are shown in experiments with rice: 68% of the grain yield was from

photosynthates produced during the reproductive period whilst 20% came from stored stem reserves.

However, the size and longevity of these organs, as well as the number and potential size of the grains, are determined during the vegetative phases. The importance of the vegetative phases is demonstrated by the effect of yellow rust, which, when it attacks the early leaves of wheat, causes a considerable decrease in the yields of total dry matter and grain (Bunting and Drennan, 1966).

Environmental conditions. Environmental conditions can affect the harvest index. Krieg (1983) reports that on the Texas High Plains, the harvest index of sorghum increases as sowing is delayed from early May until early June; the rate of development also speeds up, indicating that metabolic efficiency is possibly increased.

The water supply pattern also has a large effect on harvest index. For example, Bond et al. (1964) have shown that in sorghum, with an adequate water supply until heading, followed by drought, a large biomass was produced, but the harvest index was small; limited water supply until heading, followed by adequate moisture supply resulted in as much grain yield, with much less biomass produced. Similarly, in crops grown on stored soil water, the harvest index is related to the amount of water still available after anthesis (Passioura, 1977).

When transient photosynthesis is limited by water stress during grain filling, stem reserve mobilization assumes an important role in grain filling. A large stem reserve and/or a great capacity for its mobilization would therefore favour a high HI under drought stress after anthesis (Blum, 1990).

Bidinger et al. (1977) attribute up to 20% of grain yield to pre-anthesis assimilation in drought stressed wheat. A high transfer of assimilates to the grain maximizes harvest index and reduces the proportion of dry matter produced early in growth that is left as stover (Ludlow and Muchov, 1990).

Plant height

Borojevic (1990) points out that until the 1960's, plants with dwarf stature were considered as abnormal, and discarded during selection. They are still inferior to tall varieties under primitive production methods, with low nutrient levels, and especially in the absence of effective and timely weed control.

The reduction of stem height is generally achieved by a shortening of the internodes, leaving the number of internodes fairly constant; therefore the number of leaves and consequently LA remain unchanged. It follows that the old, tall cultivars and the new shorter ones do not differ markedly in the size of photosynthetic area per tiller or in their potential yield of biomass (Borojevic, 1990).

The most striking success in improving HI in recent years is the development of semi-dwarf wheat and rice varieties (HYVs), which are characterized by very short straw and a very large ear. This is illustrated by a typical example from a trial carried out in Israel, comparing Florence-Aurore, the standard wheat variety at the time,

TABLE 7.5

Biological and economic yields of two wheat varieties

	Y_{biol} (kg/ha)	HI	Y_{econ} (kg/ha)
Florence-Aurore	9500	0.43	4130
N67 (semi-dwarf)	9350	0.63	6220

with a semi-dwarf variety which produced the same biological yield (Ephrat et al., 1964) (Table 7.5).

The success of short-stawed wheat and barley varieties is attributed to their ability to withstand lodging and the high ratio of grain to straw. However, taller plants should be able to produce more biomass, and a positive genetic relationship has been demonstrated between height and grain yield in barley, oats, sorghum, and wheat (Wilson, 1983a). Taller plants may be better able to contribute to grain filling under stress by stem reserve mobilization (Blum et al., 1989).

Yoshida (1972) postulates that there might be an optimum height for each species and has suggested that the short stature of the high-yielding varieties of wheat and rice is not necessarily the optimum height for these crops. Borojevic (1990) suggests that extremes should be avoided, and points out that in cereals, semi-dwarfs are more productive than dwarfs.

To exploit the positive relationship between height and yield, resistance to lodging would have to be achieved in other ways than the excessive reduction of height and a high straw/grain ratio would have to be retained. Selecting positively for height, together with yield components has been proposed by Law et al. (1978) to produce 'tall dwarfs' that are higher-yielding than the 'short dwarfs'.

Dwarfness in high-yielding varieties is frequently supposed to be related to a reduced root system and therefore to cause a greater susceptibility to drought. This assumption has not been substantiated by research. Owonube and Kanemasu (1982), for example, studied the effect of height in closely related lines of sorghum and found no evidence that dwarfness restricted root development. Similar results were obtained in wheat (Pepe and Welsh, 1979).

Implications for plant breeding

Blum et al. (1983a) have indicated that there may be useful genetic variation in the remobilization of assimilates that provides possibilities for yield improvement in wheat.

Ludlow and Muchov (1990), after reviewing breeding efforts directed at improving the contribution of stem storage to the yields of grain, conclude that this trait may be of importance in stress situations, but that further work is required "to assess the consequences of this trait on yield potential and lodging in some crops, and upon

root growth and nitrogen fixation in food legumes, in particular in intermittent stress situations”.

In the 20th century, increases in wheat yield have been due to increased HI, whilst total biomass production has remained largely unchanged. Currently grown maize hybrids have an HI of 40%, compared to 25% for the old maize cultivars (Borojevic, 1990).

Donald and Hamblin (1976) point out that no plant breeder has purposely sought an increase in harvesting index; that on the contrary, any increase of HI has been an unplanned secondary effect of breeding for grain yield, shorter straw and earliness. These authors emphasize that the positive correlation between harvest index and grain yield within existing cultivars does not provide evidence of the value of this index as a selection criterion, but it seems that it may be a valuable criterion for early generation selection among spaced plants; at normal crop density vegetative characteristics may be more useful. They further recommend that the selection of parents in breeding programmes should be extended to include material of high harvest index, even involving genotypes of lower biological yield, on the assumption that within each of the cereals there may be unknown sources of high harvest index, that are overlooked because their production is low. There is also the possibility of combining a high biological yield with a high harvest index.

When the first commercial sorghum hybrids were released in the late 1950's, the sorghum breeder J.R. Quinby predicted that no future hybrid would outperform in yield the outstanding hybrid Rs610 (personal communication). More than three decades later, this prediction has apparently not lost its validity (Blum, personal communication).

Arnon and Blum (unpublished data) found that Rs610 combined the high biological yield of the female line and the high harvest index of the male line, as shown in Table 7.6.

Though probably unplanned by the breeder, it would not be far-fetched to assume that the success of Rs610 is largely due to the fortunate combination of high Y_{econ} and high HI.

It is generally agreed that grain yield improvement has not resulted from any significant improvement in the biochemical or physiological constitution of the plants (Blum, 1988); the large yield increases achieved in modern agriculture are

TABLE 7.6

Biological and economic yields of Rs610 and of its parent lines (dryland, stored moisture)

		Y_{biol} (kg/ha)	HI	Y_{econ} (kg/ha)
Female line	6062	746	0.51	3840
Male line	7078	547	0.64	3510
Hybrid	Rs610	728	0.65	4680

mainly due to the greater proportion of biomass that is converted into the economic product, e.g., raising the harvest index, rather than to increases in total dry-matter production per se (Gifford et al., 1984).

The potential to further increase harvest index depends on the crop and the remaining scope for improvement (Evans, 1983). It is, of course, greatest in those crops in which it is still relatively low, as in soybean. Austin et al. (1980) claim that it is possible to increase the HI of wheat from the present 50% to about 60%, without changing the above-ground biomass.

Hay and Walker (1989) argue that further reductions in the stem component of biomass might be counterproductive in view of the stem's role in supporting the ear and maintaining an effective display of leaves. In their view, increases in biological yield, while maintaining current highest HIs, offer the best prospects for further increases in yield.

Krieg (1983) states that many crop physiologists also believe that in many crop species the upper limit of harvest index improvement has been approached, and that further yield increases will depend on increasing the photosynthetic rate per unit leaf (cf. p. 284). This view is also held by plant breeders: Blum (1988) opines that the present route by increasing harvest index is finite, unless a genetic way is found to increase biomass.

To achieve further increases in biological yield, the most promising course would be to increase NAR; increasing leaf surface would entail higher water requirements which would make this approach counterproductive especially in drought-prone areas (Hay and Walker, 1989). It has been pointed out in a previous section that attempts to increase dry-matter production by breeding for improved NAR have hitherto been largely unsuccessful (cf. p. 296).

Yield components

In many crops, economic yield is the result of "a series of sequentially determined yield components, each of which is the result of source-sink relationships operating during successive phases of plant development" (Hay and Walker, 1989).

Attempts have been made to achieve better understanding of the economic yield of many crops, so as to provide selection criteria for breeding purposes, by breaking down yield into yield components. We have taken grain cereals, and in particular wheat, as representative examples of this work, because it is the best-documented.

A familiar formula of yield is that for grain cereals:

$$Y = a \times b \times c \times d,$$

in which Y = grain-yield per unit area, a = the number of plants per unit area, b = the number of fertile tillers per plant, c = the number of grains per ear, and d = the weight of the individual grain.

At first sight, an increase in one of the components on the right-hand side of the

equation should lead to an increase in yield. This expectation has led, in the past, to a considerable amount of attention being paid by plant breeders to these factors in the hope that yields could be increased by combining, in a single genotype, a combination of components such as increased tillering capacity, large ears, heavier grain, etc. This requires an understanding of the influence of the various components on yield, and the effect of crop management on each of them.

Number of plants per unit area

This subject will be treated in detail in Ch. 15.

Tillering

The number of stems per unit area is the first yield component developed by cereals, and it is therefore essential to ensure an optimum density of tillers/m² for each genotype and environment (Borojevic, 1990).

The temperate cereals often produce tillers far in excess of the number eventually bearing ears. Consequently, up to two-thirds of the tillers may be wasted, but this wastage does provide for possible compensation early in the life cycle (Evans and Wardlaw, 1976). It has been shown in wheat that recovery by new tillers can lead to very reasonable yields (Hochman, 1982).

Tillering also adds to plasticity at later stages, because flowering of tillers is progressive over time, and can thus compensate for transient stress damage to earlier tillers. Hanson and Nelson (1980) point out that this may be particularly important because anthesis and fertilization have little plasticity due to their brief and sensitive nature. Conversely, transient drought stress after tillering causes tiller abortion (Blum and Pnuel, 1990).

Most cereals have a considerable capacity to increase the number of tillers per plant, when sufficient space is available to the individual plant. An optimum number of ears per unit area can therefore be achieved in two different ways: by a low plant density, compensated for by an increased number of fertile tillers per plant, or by a high plant density, which will keep the number of tillers per plant low. At first glance, the former approach appears to be the more rational: savings in seed can be achieved by it, and the plant will autoregulate the number of ears per unit area according to whether environmental conditions are favourable or not.

In practice, however, this approach has a number of drawbacks. Thus a sparse stand is more susceptible than a dense one to weed infestation, and unfavourable conditions may reduce plant population below the point at which increased tillering can compensate for missing plants. The principal limitation, however, is that the tiller is not an independent unit: it is considerably influenced by other tillers produced on the same plant. There is, therefore, a great difference in principle, in whether the number of ears per unit area is derived from a large number of plants with a few

fertile tillers each or from relatively few plants with abundant tillers. The following considerations seem most pertinent in these connections.

Fertile tillers per plant. The first genetically controlled component of yield is the number of fertile tillers (i.e. ears) per plant. The optimum number is, of course, closely dependent on the moisture régime during the growing period of the crop. In wheat variety trials in a wide range of variable moisture régimes in a Mediterranean environment (230 to 755 mm) Blum and Pnuel (1990) report that the only yield component significantly associated with precipitation was the number of fertile tillers (i.e., number of ears) per unit area.

(a) The ear-bearing capacity of an individual tiller depends on the number of tillers per plant. A negative correlation is known to exist between tiller production and tiller survival, indicating the existence of a regulatory mechanism which keeps the rate of ear production per plant down to a determined level (Frankel, 1935). It has been shown that only tillers formed before a certain period in the life of a plant will produce ears (*ibid.*). Therefore, on the same plant, tillers appearing at a relatively late date will have less chance of producing ears.

The final number of ears per unit area can therefore be achieved by increasing either tillering or the proportion of those tillers that survive and produce ears. There appears to be better justification to produce fewer tillers and increase the survival rate than vice versa.

(b) The primary tiller usually produces the largest ear, each successive earbearing tiller producing ears of decreasing size. The second and third ears are generally nearer in size to the first ear than are the subsequent ones to be formed. The tendency in recent years has therefore been to breed for varieties with sparse tillering capacity but higher ear-producing tiller survival, and to plan plant density so as to decrease dependency on tillering as a means of achieving optimum density. However, retaining a limited ability to tiller (two to three tillers per plant) enables auto-adjustment of the plant according to environmental conditions and compensation for missing plants, without adversely affecting the ultimate yield.

The ultimate solution to this problem would be a stand composed entirely of plants with a single stem, carrying a large ear. Wheat and barley lines in which tillering is inhibited to varying degrees, including ones with a single stalk ('*uniculm*') became available to plant breeders in the 1970's (Richards, 1988). These lines have, as yet, not given rise to commercial varieties, despite the fact that *uniculm* plants are taller, earlier flowering, and have thicker stems, larger leaves and ears, and more grains per ear than normally tillered cereals. According to Richards (1988), the lack of progress in incorporating *uniculm* genes is possibly because they have some defects. Some 50 years earlier, Frankel (1935) had already pointed out that one-ear plants may produce smaller ears than two-ear plants, mainly because the former are weak or dis-

eased. According to Richards (1988), the unculm trait often causes developmental abnormalities.

In brief, temperate cereal types with tillering potential limited to two to three stalks appear to be the most promising, in particular for growing in drought-prone areas. Their major advantage is a lower LAI in the period before anthesis, resulting in more water being available for grain filling, hence a higher harvest index and grain yield (Richards, 1988).

The ear is not just a structure for carrying the reproductive organs, it also makes a significant contribution to photosynthesis, that is of special importance in stress situations. In reviewing the work of several authors, Blum (1985) indicates that the better ability of ears than of leaves to supply assimilates to the developing grain during drought stress is partly due to the greater availability to the grain of ear assimilate than of flag-leaf assimilate; spikelets maintain a higher tissue water potential and more effective osmoregulation than leaves during the stress.

Awns

The awns contribute to the total photosynthesis in proportion to their total relative area in the ear. Depending on the amount of awns, total photosynthesis by the ear may contribute to increasing yield by up to 10% (Borojevic, 1990). Furthermore, the advantage of awns is most marked under conditions of water stress: Evans et al. (1972) found that awned wheat plants significantly outyielded awnless plants under dry conditions, but did not perform better than the latter under humid conditions.

Number of grains per ear, and weight of individual grains (or parallel structures)

Source-sink relationships. Plant growth is a function of the integration of two basic activities (Krieg, 1983):

- source activity, e.g., effective leaf area $\times$ photosynthetic rate; and
- sink activity, e.g., number of growing sinks $\times$ rate of incorporation of dry matter.

Sinks are defined as net importers of photosynthates (Hay and Walker, 1989). Different types of sinks function at different stages of plant development. During very early growth, the major sinks are the growing leaves and roots. Later, the stalks begin to compete for assimilates. In the last stage, storage organs, such as seed, are the dominant sinks.

Which of the two activities – photosynthetic activity or storage capacity – is the major determinant of yield is still being debated. The most probable answer is that both source and sink can limit yields, but that either can predominate, according to circumstances (Gifford et al., 1984). If photosynthesis is allowed full expression, sink limitation generally prevails (Hay and Walker, 1989).

The effect of sink size on source activity has been studied quite extensively. There is evidence in many plants that if all the fruits or seeds initiated were to develop, photosynthesis would be incapable of supplying sufficient assimilates for their nor-

mal development. In cotton, for example, usually less than 20% of the flowers and 40–60% of the young fruit actually result in harvestable yield. Shedding of potential fruit (squares) and actual fruit (young bolls) is therefore a mechanism whereby sink availability is adapted to source activity (McMichael, 1979).

The assimilation capacity of the plant depends to a large degree on the utilization rate of the metabolites produced. Wareing et al. (1968) demonstrated that the rate of photosynthesis is modified by the availability of sinks for the photosynthates produced, by removing some leaves and showing that the remaining leaves increased their rate of photosynthesis.

Other workers have used inflorescence removal or de-graining as an experimental tool to study source/sink relations. Blum et al. (1988) reduced sink size by de-graining half the ears of wheat. The resultant smaller sink clearly reduced source activity. The contribution of leaf carbon exchange rate and stem reserves was consistently reduced by de-graining under stress conditions. Grain weight compensated for the decrease in grain number, generally higher in de-grained than in whole ears.

Geiger (1976), from his own work and an extensive review of the work of others, concluded that an indirect mechanism is involved in the rapid changes in leaf photosynthetic activity as a result of modified source strength. Probably, hormonal control, rather than a feed-back mechanism, is involved in the process.

Increasing the productivity of the plant, in terms of increased carbohydrate production, will contribute to increased yields only if the total storage capacity of the plant is adequate – e.g., in the case of cereals if a sufficient number of grains are produced and their development is adequate; in other words an adequate ‘sink’ is required, that is capable of receiving the carbohydrates in excess of the current metabolic needs of the plant.

Grain number and size (in wheat). In general, factors acting early in the season mainly influence the grain number, whilst the size of grain is determined mainly by factors acting after anthesis, such as the quantity of assimilate available for transport to the ear between anthesis and maturity (Bidinger et al., 1977). This in turn depends on green leaf area duration, photosynthetic activity of the ear, and source/sink relationships (Hay and Walker, 1989).

In seasons when LAD is low because of drought, significant amounts of assimilates stored in the stems and leaf sheaths before anthesis may become available to the grain (ibid.). In breeding wheat for drought resistance, it was found that when soil moisture was adequate, the yield component which had the greatest effect was number of ears per unit area; under conditions of moisture stress the grain number per ear and, occasionally, average grain weight, had as much effect as the number of ears. Asana (1962) therefore suggested grain number per ear and 100-kernel weight as criteria for selecting varieties for dryland wheat production.

In the trials by Blum and Pnuel (1990) mentioned in a previous section, it was mean number of ears/m² that was most closely associated with precipitation; whilst over the

whole range of precipitation it was kernel number/ear that was the most important yield component affecting yield variations among cultivars; ear number/m² was second in importance, while kernel weight had the least significant effect.

In these trials, drought stress developed about a month before heading, followed by a recovery period during grain filling. Under these conditions, ear number was reduced mainly as a consequence of increased tiller abortion under drought stress. Cultivars that performed better under *these* drought stress conditions apparently had a better capacity to compensate for reduced ear number by sustaining a high number of kernels per ear.

The contrasting results reported by Asana (1962) and Blum and Pnuel (1990), respectively, are probably due to the effect of drought stress at different periods of development, and illustrate the difficulties of drawing general conclusions when these refer to such an inconsistent environmental variable as drought stress.

In semi-arid regions, seed weight may be relatively more important than in more favourable environments. After seed number has been reduced by moisture stress, the only way plants can compensate when the transient stress is alleviated, is by increasing seed weight (Eastin, 1980). This is illustrated by the results of an experiment by Tufail (1971) in which the removal of 23% of seeds in sorghum resulted in a 24% increase in seed size (weight); when 51% of the seeds were removed, seed size increased only 38%, so that yield was decreased.

Significance for plant breeding

In grain crops, breeding for restricted tillering could reduce wasteful use of water in dry conditions, and increase harvest index (Blum, 1973); this could be achieved without necessarily foregoing the ability of the plant to compensate in thin stands, if plants are developed with a few tillers, instead of the abundance of tillers characteristic of many varieties; unicalm plants would not be advantageous in this respect.

Summing up, the need for sufficient tillers, either for survival or compensating for missing plants, requires, in practice, a compromise solution.

Attempts to obtain high-yielding varieties by combining high tillering capacity, large ears and large kernels into a single genotype, have generally not been successful. Fonseca and Patterson (1968) studying the heritability of components of yield in winter wheat, found that the three components were highly correlated with grain yield. Though each of the components had a direct effect on yields, it was the negative correlation between number of ears and number of kernels per ear that hampered the selection of components for increasing yields.

The maximum yield that can be achieved under given environmental conditions has a ceiling that cannot be surpassed. Therefore, at a certain yield level, compensating reactions take place, and compromises in the degree of component traits become necessary.

For example, in hybrid barleys, grain number was increased under the effect of heterosis, but yield was not affected, because grain weight decreased due to competi-

tion within the ear (Carleton and Foote, 1968). From the foregoing, Borojevic (1990) concludes that “maximum yield is the realization of the most favourable balance among yield components”.

Evans and Wardlaw (1976) consider the capacity of cereals for yield component compensation, which enables them to compensate for earlier losses or restriction of development, or to take advantage of favourable conditions late in the crop life cycle, as one of the reasons for the success of cereals as crops.

Overall, the high yield potentials that have been achieved by plant breeding are the result of maximizing the interception of PAR and increasing harvest index, without paying attention to the components of yield (Hay and Walker, 1989). Using yield components as selection criteria in breeding for yield is not widely used (Borojevic, 1990). Frey (1971) gives the following reasons: (a) the relationship between yield and its components is not always linear; (b) the relationship is influenced by environmental factors; and (c) it is sometimes more difficult to evaluate yield components than yield itself.

Ideotypes

Donald (1968) pointed out that plant breeding in the past had been based mainly on defect elimination or selection for yield. He suggested that further progress could be achieved by defining model plants that would combine physiological characteristics that were known to influence photosynthesis, growth, and the harvest index.

As an example of such an ideotype, Donald described what he considered to be the ideal wheat plant for environments where water and nutrients were non-limiting. The plant was to have a single short, strong stem, with a few small, erect leaves; a large awned ear, with many florets per unit dry matter of the tops.

With one exception, the single stem trait (uniculum), Donald's wheat ideotype correctly described the high-yielding varieties of wheat which were being developed by Borlaug (1965) and co-workers. These were to become so dramatically successful that the replacement of traditional varieties by the new so-called ‘miracle’ wheats became known as the Green Revolution, and earned a Nobel Prize for the leader of the breeding programme. What might, at first sight, appear to be a vindication of the ideotype concept, actually proved the opposite. Varieties bred by traditional methods, involving “hybridisation among promising parents, the production of segregating populations, and the selection of high-yielding material from among the segregates”, the very approach that the Donald's model was to replace, resulted in an ideotype and not vice versa.

Notwithstanding the interest kindled by the novel approach to breeding suggested by Donald, the inherent logic of the ideotype concept, and the intellectual attractiveness of working towards a model based on physiological knowledge, the author's hope that “eventually most plant breeding may be based on ideotypes” was not realized in the years that followed.

The main constraint to achieving success through breeding for an ideotype is mentioned by Donald (1968) himself, namely the wide array of compensating mechanisms for high yields makes the definition of a model potentially hazardous, by narrowing the spectrum of a breeding programme, rather than permitting the emergence of the highest yielding segregates without prejudice by the breeder as to the most desirable plant form. One such prejudice is the inclusion of the unicum concept, a major flaw in the wheat ideotype proposed by Donald (1968) (cf. p. 304).

Rasmusson (1984) states that he had not succeeded in obtaining higher-yielding barley cultivars by selecting on the basis of an ideotype and illustrates the difficulties encountered by the plant breeder working towards a preconceived plant model:

When selecting for a large ear number, the seeds were few in number and small, and lodging was increased; selection for semi-dwarf height (*sdw* gene) was associated with small seeds, late maturity and poor malting quality; selection for erect leaves improved lodging resistance but resulted in late maturity. His conclusion: "the plant breeder is precluded from breeding the ideotype of his choice, i.e., some combinations of characters are not morphogenetically compatible".

Conclusions

In conclusion of a comprehensive review of the state of the art in breeding for morphological and physiological traits Evans (1983) makes the following recommendations as priorities for the foreseeable future:

- define the optimum canopy structure for each crop;
- determine the most appropriate management to maximize the effect of this canopy structure on yield;
- define the strategies and forms of genetic adaptation to environmental variables;
- devise methods of easily assessing genetic variation in phenotypic adaptability;
- determine the optimum harvest index of the major crops;
- resolve the puzzle of photorespiration;
- examine the wider implication of breeding for reduced losses from dark respiration.

Evans concludes his review with the optimistic statement that "increasing knowledge of the physiological basis of yield and adaptation will continue to improve our ability to more accurately identify the most suitable genetic material to be the parents of the cultivars of the future".

Breeding for heat tolerance and cold resistance*Breeding for heat tolerance*

High-temperature stress may be a major cause of yield loss in many crops, and yet little specific effort has been invested in breeding for resistance to heat stress (Marshall, 1982). A number of factors combine to make this a difficult objective to achieve; among these Marshall (1982) mentions the limited understanding of the genetic and physiological bases of heat tolerance in plants, and the lack of efficient and accurate laboratory tests to select for the physiological traits for heat tolerance. Field tests in the natural environment, for line testing and selection, has limited value, because it is impossible to separate the effects of heat and drought stress.

For most crops, evaluation of germ plasm for heat tolerance has been limited; however, genetic variation for heat tolerance is present in several important crop plants, and has been shown for germination, growth during heat stress, growth recovery after heat stress, photosynthesis, translocation, fruit or seed set, and stability of cellular membranes (Blum, 1988).

Marshall (1982) concludes that the breeder may occasionally be successful in developing a variety that shows heat tolerance by empirical selection under field conditions; also, that breeders had made indirect gains for heat tolerance by selection for higher yields or plump grain.

A similar conclusion has been made by Blum (1988), who states that the simplest approach to selection for heat tolerance would be to utilize the natural stress field environment.

Breeding for cold resistance

Since the beginning of this century, selection for winter hardiness was performed on the basis of repeated evaluations over a wide range of cold environments, mainly in the semi-arid middle-latitude regions of North America and the USSR. Many of the old wheat, barley and oat varieties, bred in this way, had excellent genetic tolerance for freezing, and are currently still being grown (Blum, 1988).

A plateau for winter hardiness appears to have been reached, and there is little evidence among modern varieties of further significant increases in winter hardiness. However, breeders have incorporated important traits, such as lodging resistance, disease resistance and yield in the most winter-hardy domestic wheats (Marshall, 1982).

Among forage crops, the major breeding effort for cold tolerance has been with lucerne (*Medicago* spp.).

Various physiological adaptations occur during cold hardening, but it has not been possible to use these relationships in breeding programmes "because many of the cause and effect relationships of plant response to low temperatures remain unclear"

(Marshall, 1982). Nor have sufficiently accurate or efficient laboratory selection techniques been developed (*ibid.*).

Genetic variation in chilling tolerance is found for various physiological processes such as photosynthesis, plasma membrane function and for different plant functions. Most of the information is available for seed germination and seedling establishment (Blum, 1988).

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PART III

Land Use and Farming Systems

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CHAPTER 8

Agricultural Systems in Dry Regions and Their Evolution

The beginnings of agriculture in dry zones

For about half a million years, Man subsisted by gathering 'wild' food, hunting and fishing. About 10 000 years ago, Man started producing food in several areas of the world. Cohen (1977) concludes that this can only be explained by assuming that gradually increasing hunting and gathering populations had exhausted available food supplies. Other explanations have been proposed, and Lawton and Wilke (1979) conclude that "the causes for the development of agriculture are probably complex, vary from region to region, and are likely to remain elusive for a long period to come".

One undisputable fact that emerges from research on the origins of agriculture, is that most early agricultural economies developed in the drier regions of the world. This is true for the centres of origin of the new technologies (in the Near East, in Peru, in southern Mexico) as well as the recipients of these technologies that had diffused from the centres of origin (the Nile Valley, American Southwest) (ibid.). This occurred notwithstanding the fact that agriculture in semi-arid areas is beset by problems not faced in more humid climates, or by irrigated agriculture in the arid regions; the major problem being the uncertainty and risk due to the variability of precipitation from year to year and from location to location.

In the Old World

Domestication of plants and animals

About 10 000 years ago, Mediterranean Man started producing food in the Near East, first in the highlands and plateaux which flank this region and subsequently in the drainage basin of the Euphrates and Tigris.

As a result, three great cultural-historical events occurred in this region: the earliest appearance (i) of the use of blade tools, (ii) of settled village farming communities based on cereal agriculture and animal domestication (about 10 000 years ago), and (iii) of urban civilization based on irrigation agriculture (about 5000 years ago)



Fig. 8.1. Natufian blade sickle (about 7th millennium B.C.) indicates that Natufian man was not only a food gatherer, but also a food producer (Albright, 1956). By courtesy of the Israel Museum, Jerusalem.

(Braidwood, 1952). All the available evidence indicates that the first efforts at domestication were devoted to the growing of cereal grains (Braidwood and Reed, 1957).

Helbaek (1959) postulates that domestication of a wild plant must have taken place within the region of its natural distribution. In the Near East* both wheat and barley were grown concurrently for bread. The probable progenitor (*Hordeum spontaneum*) of domesticated barley is found over a wide area, practically from Turkestan to Morocco, whilst that of domesticated wheat (*Triticum dicoccoides*) is restricted to a much smaller area, situated within the wider range of wild barley. It can therefore be assumed that plant domestication in the Old World originated in this restricted area,

*Near East. This term was formerly used to denote the Balkan States and the area of the Ottoman Empire. Since the Second World War, it is commonly used as an alternative for 'Middle East', encompassing the region of S.W. Asia and N.E. Africa stretching from Turkey through Iran, Iraq, and Arabia to the Sudan and countries bordering the E. Mediterranean. It is in the latter sense that the term Near East will be used in this work.

situated between the Zagros Mountains (Iraq, Iran), the Taurus Mountains in southern Turkey, and the uplands of Galilee (Petersen, 1965).

The earliest evidence of harvesting of wild grains of emmer wheat and barley, 15 000 years ago, was found at Kebara and later levels of Nahal Oren in Israel (Noy et al., 1973) (Fig. 8.1).

Evidence of the earliest appearance of kernels of partly domesticated forms of wheat, barley, and several pulses, was found in the excavations at Jarno, a village in Iraqi Kurdistan. These findings indicate that partly domesticated grains were already used for human consumption in the seventh millennium B.C., although actual cultivation at that time has not yet been proven. However, at the village site of Matarrah, at a lower elevation than Jarno, only *cultivated* emmer wheat was found (Helbaek, 1959); these findings belong to the sixth millennium B.C.

The Natufian culture of Palestine (approximately 7th millennium B.C.) used flint sickle-blades with stone or bone shafts (Fig. 8.1) as well as hoes for loosening the soil before sowing, indicating that Natufian Man was not only a food gatherer but also a food producer (Albright, 1956). Though the Natufians were cultivators of grain, they apparently continued to gather wild food, to fish, and to hunt.

It is generally agreed that the domestication of food animals occurred at a somewhat later date than incipient plant cultivation.

Early agriculture in the Near East

After 6000 B.C., food production and animal husbandry were well established throughout the Near East. The major crops included bread wheat, emmer, einkorn, barley, pea, lentil, chickpea, vetch, flax, and by the Early Bronze Age, grape and olive (Lawton and Wilke, 1979).

In the early days of crop domestication, the cultivation of cereal grains was practised at higher elevations, where there is relatively ample winter rainfall. However, as crop cultivation involved tilling the soil, it became imperative for the early cultivators to move down from the natural habitat of wheat on the mountain slopes, to the lower and more easily tilled land, searching for sites with adequate rainfall for the crops and a good water supply for domestic needs and for the establishment of the village farming communities which characterized the agrarian structure (Reed, 1959). During the Neolithic period (sixth to fifth millennium B.C.) settlements developed wherever springs made this possible – usually on foothills near fertile plains.

As population increased, the initially small area of crop domestication expanded, and it was necessary to move from the open-forested slopes of Mesopotamia, Syria, and Palestine, to the alluvial plains. This movement, from the fringes of the semi-arid area to the arid areas of the region, was possible only by resorting to irrigation. In the sixth millennium B.C., there is evidence of large-scale cultivation of emmer wheat under irrigation in the alluvial plain of lower Iraq, after the people had learned to dig canals and build dams in order to divert water for irrigating large areas, beginning what Albright (1956) called 'irrigation agriculture'.

From the Near East, this agrarian culture spread throughout Asia Minor, to Egypt, the Indus Valley (late third to early second millennium B.C.) and the Far East (Helbaek, 1959). Crossing to Europe also came relatively early: from its centre in the Near East, agriculture diffused north from Greece up the Danube and down the Rhine Rivers; at the end of the fifth millennium B.C., einkorn and emmer wheats were already cultivated on the large loess plains ranging from the Danube Delta to the mouth of the Rhine (Reed, 1977).

Early agriculture in China

It is generally agreed that agriculture arose independently in China. The earliest evidence dates back to the fourth millennium B.C., the centre appears to have been in the semi-arid loess highland of the Wei River basin in northern China. The main crop was setaria millet (Ho, 1977).

As agriculture expanded outward from this centre, other crops, such as rice and soybeans, were added. The earliest known site for domesticated rice is at Sung-tse, which dates to about the third millennium B.C. According to archeological evidence, rice was probably first grown on marshy areas, by broadcasting the seed on submerged land and then allowed to grow without weeding or manuring (Ho, 1977).

Early agriculture in the New World

Domestication of plants occurred about the same time in the New World as in the Old World, although a full-time dependence on agriculture came much later (Lawton and Wilke, 1979). The first cultivated plants, squash (*Cucurbita* spp.) and bottle gourd (*Lagenaria siceraria*) were domesticated in the New World almost at the same time as wheat and barley in the Near East (Pickersgill and Heiser, 1977).

This development occurred on lines very similar to those that characterize Neolithic agriculture in the Old World.

The domestication of plants and other important cultural developments in the New World occurred in the arid regions of Central and South America (Woodbury, 1963). The two main zones in which the most important New World crops originated are in the Mexico–Guatemala region, and the Andean region in the south (Armillas, 1956). Hunting and food gathering continued for a long time to provide the main sources of food – even after plant domestication made incipient farming possible – and were still being practised up to the 19th century by the Indians in Utah and Nevada, indicating an extremely successful subsistence adjustment to their arid climate (Woodbury, 1963).

The earliest evidence for incipient agriculture in the New World (7000–5000 B.C.) comes from the semi-arid hill country of Tamaulipas, north-eastern Mexico, and consists of traces of domesticated squash and possibly domesticates of peppers and small beans. Considerably later (between 3000 and 2000 B.C.), a primitive small-eared maize appeared in the same area, where fully settled village farming is evi-

denced from about 1500 B.C. From thereabouts village farming, based on cultivated food plants, spread northwards to Mexico and southwards as far as Peru, with the maize plant as the vital element, complemented by beans and pumpkins (Willey, 1960). By 700 B.C., a relatively well-developed type of maize appeared also at Hauca Prieta in Peru, indicating that links had been established between the farming villages of Middle America and Peru (ibid.).

The oldest villages with archaeological evidence of farming are found at elevations at which rainfall was sufficient for growing rain-fed crops. There is also evidence of early farming on the Gila River in Arizona, where there is an annual precipitation of only around 250 mm; it is assumed that the local Indians planted their crops in the wet margins of the river after the floodwater had receded (Woodbury, 1963). About 300 B.C., the earliest irrigation canals were constructed, which took water from the Gila River. The major crop was maize, but later more crops were added: the common bean (*Phaseolus vulgaris*), cotton, squash and tepary bean (*P. aconitifolius*) (Haury, 1976).

As in the Old World, the expansion of irrigated farming necessitated the establishment of a strong central authority. This occurred in the New World in Peru and Mexico between 500 B.C. and 500 A.D.

General patterns of land use in the dry regions

Throughout the historical period, certain patterns of land use have evolved that characterize the agriculture of the dry regions of the world. These patterns are extraordinarily similar over very wide areas, notwithstanding the great diversity due to various combinations of topography, soil type, and climate. Land use has also shown a surprising amount of stability, having remained practically unchanged in the Old World throughout the historical period – even to the present day, see Fig. 8.2.

From the agricultural standpoint, arid areas are those in which rainfall is not sufficient for crop production, whilst in semi-arid areas rainfall is sufficient for adapted crops. In the desert areas as such, the only agricultural use is grazing of the sparse plant cover by livestock; pastoral agriculture is therefore the dominant form of land use of vast expanses of desertic terrain.

Crop production in deserts becomes possible only with irrigation, whether by flash floods, annual inundation, or a year-round water supply. In the semi-arid regions, rainfed crops can be grown with a reasonable degree of security – the risk of complete failure of the harvest is in general not greater than two years in ten – but the low and erratic rainfall limits the number and variety of crops that can be grown, as well as their yields. Cereal cultivation is the main source of livelihood.

The amount of rainfall that has been set, somewhat arbitrarily, as the limit of regular dryland farming, is around 250–300 mm in areas with predominantly winter rainfall, and approximately 500 mm for areas with summer rainfall (Wallen, 1966).

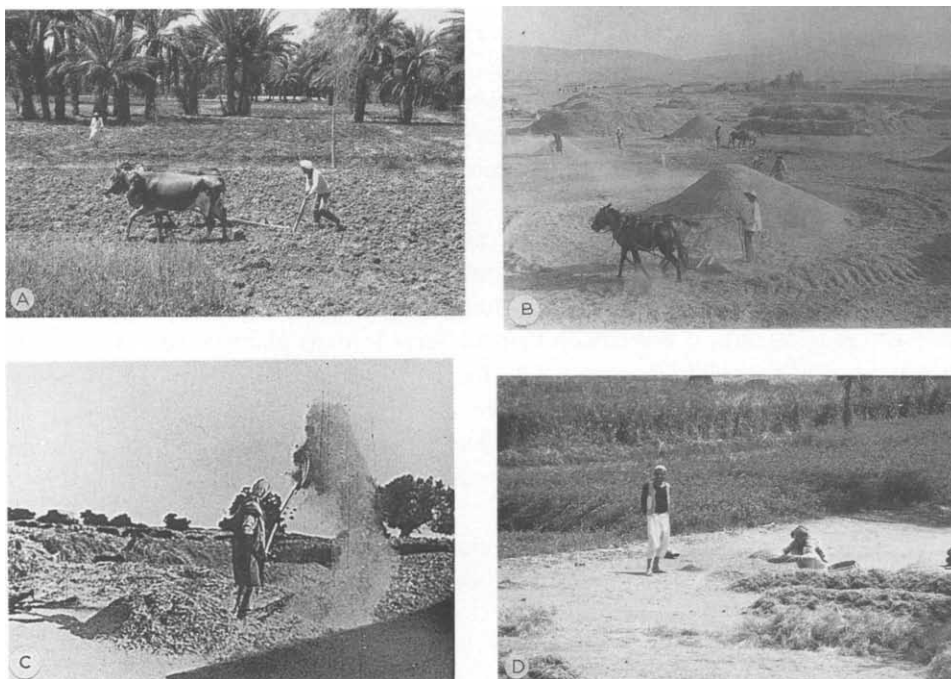


Fig. 8.2. Biblical agriculture is still practised in the 20th Century. (A) Preparing a seedbed in Egypt. Note the similarity of the wooden plough used with that depicted in Fig. 14.1. Photo D. Arnon, 1990. (B) Threshing floor in the Middle East. The threshing board is identical to the “threshing instrument having teeth” of Isaiah (41.15): “the ox who treadeth the corn” (Deut. 25.4) is frequently replaced by mules. (C) “Behold, he winnoweth barley to night in the threshing floor” (Ruth 3.2). “Though shalt fan them and the wind shall carry them away” (Isaiah, 41.16). Photo Soil Conservation Service, Israel. (D) “Like as corn is sifted in a sieve” (Amos, 9.9). Photo D. Arnon, 1990.

The closer arable crop production is practised to the fringes of the desert area, the more precarious and uncertain it becomes.

Sedentary agriculture

Sedentary agriculture established itself early in large, contiguous areas along great rivers such as the Nile, the Tigris, the Euphrates, and the Indus. It also became established in isolated pockets of well-watered oases of the deserts, more precariously on the floodplains of the streambeds in the deserts, and in places on the semi-arid fringes of the deserts where rainfed crops were produced.

This pattern of land use has led to a virtual separation of arable cropping from animal husbandry. Conflicts between the nomadic pastoralist and the sedentary cultivator are a recurrent theme in the Old World throughout the historical period, as characterized by the biblical strife between Cain and Abel. This theme repeated itself

in the New World, when the arid regions of the American West were first settled by the White Man.

The lot of the sedentary cultivator in the dry regions was always precarious and hard. Even when the water supply was fairly adequate and assured, irrigated crop production was associated with backbreaking labour in a difficult climate and under unsanitary conditions.

The primitive irrigation farmer, in addition to typical agricultural operations – such as soil preparation, sowing, weeding, and harvesting – was burdened with additional backbreaking chores, of which the actual watering of the crops was the most onerous. The maintenance of the irrigation system – canals, ditches, levees – also involved unending drudgery. Weakened by malaria and bilharzia and other diseases endemic to the irrigated areas, the cultivator was under constant pressure from the nomads. His life was also made difficult and bitter by a social environment that was based on the exploitation of his labour. Most of the available arable land in the oases and water-spread areas of the Sahara and the Sahel, for example, was, and still is, owned by Arab or Berber nomads. The land is worked by share-croppers of Negro slave origin (Haratin) or impoverished Berbers; for their work they receive about one-fifth of the crop (Monod and Toupet, 1961).

The maintenance of the irrigation system required an enormous amount of manual labour. Right up to the end of the 19th century, the fellaheen in Egypt were required to clear, without pay, the mud that had accumulated in the irrigation canals (*corvée*). This they did by scooping the mud from the canal bed with their hands and dumping it on the high banks of the canal (Addison, 1961). Even the agriculture which they practised was beset by difficulties: irrigation increased the hazards of pests and favoured the proliferation of diseases; the fragile soils typical of the arid regions broke down easily under irrigation; and rising water tables and salt accumulation imperilled the very basis of their livelihood. Paradoxically, the cultivators who were dependent on the erratic rainfall of the region, whether in the production of rainfed crops or by utilizing flash floods, were generally better off than those practising typical irrigation agriculture. In Biblical times, the Israelites considered it a special blessing that they were not compelled to irrigate as in Egypt, but could depend on rain and dew for growing their crops (Reifenberg, 1953).

Nomad pastoral agriculture

By contrast, the nomad pastoralist appears to have achieved a far better balance with his environment than did the sedentary cultivator. His basic livelihood and indeed his whole way of life, was dependent on his flocks. Camels, sheep, and goats, are able to subsist on the sparse vegetation of the desert. They are able to travel relatively large distances to water; they can also use water of high salinity that is unfit for human use or even for irrigation.

His flocks provided the nomad with drink, protein foods, and the materials needed

for clothing and shelter. They were mobile, and so the nomad could adjust to the vagaries of the arid climate by seasonal movement of the livestock in search of pasture and water. He also had additional sources of income: he had gained a virtual monopoly for transportation over the traditional desert routes – such as the trans-Saharan slave trade from tropical Africa to the Mediterranean, and the ancient ‘Silk road’ between China and the Near East. Levies exacted from pilgrims and merchants travelling on the desert routes, tribute from cultivators working the nomad-owned land in the oases on a share-cropping basis, plunder from slave-collecting razzias and other raids, augmented the income of the nomad tribes, even though they were not equally divided among all its members.

With the aura of romanticism that usually surrounds the nomad way of life in the desert, it is tempting to overestimate the degree of adaptation of the nomad pastoralist to his environment. A balance was indeed achieved, but at a very low standard of living for the vast majority of the tribal members. Though the Bedouin does not generally engage in the same backbreaking labour as the fellah, his life is arduous and knows many discomforts and dangers. The balance between livestock and the forage resources of the desert is also very precarious, notwithstanding the mobility of the pastoralist and his flock. A longer-than-usual period of drought might wipe out a large proportion of his herds, especially the young stock. After a period of relative abundance, the numbers of his stock might grow out of all proportion to the normally available forage resources, and overgrazing might follow before a balance was again achieved by an increased mortality rate. The nomads did not normally slaughter their animals for food, the herds being considered as non-expendable capital – thereby preventing any planned adjustment of livestock numbers to available forage. The nomads also suffered, and still suffer, from many diseases.

Conquests and their aftermath

On the basic theme of conflict between nomads and sedentary farmers, was superimposed a sequence of conquests and their aftermath, which is repeated throughout the history of the arid regions. The names of the invaders and the dates may differ in different regions, but the basic sequences are very similar. The invaders were of two types: nomads – such as, at various periods, the Seljuks, Turkomen, Mongols, Uzbeks, and Arabs – and well-established empires such as those of Babylonia, Persia, Greece, Rome, Byzantium, etc.

After a preliminary phase of destruction during the conquest, the cultivable land was subsequently allocated as spoils of war to warriors in whose interest it therefore was to further agricultural production. However, the agricultural population, already decimated by the conquest, was submitted to heavy taxation and oppression, generally by corrupt administrations. Heavy levies, needed to maintain the armies, were exacted. In order to counteract the tendency of the agricultural population to abandon the land and concentrate in the towns, laws were enacted binding the culti-

vators to the land, transforming them into semi-serfs and serfs. Another solution was to employ slave labour on the large estates of the big landowners.

A typical example of the consequences of large-scale invasion by nomads is that of Cyrenaica, which up to the 11th century had developed a fairly prosperous agriculture. The invasion of Arab nomads in the 11th and 12th centuries resulted in the almost complete extinction of sedentary farming (Despois, 1961). By contrast, after the Roman conquest of the Levant and of North Africa, the Romans established fortifications (limes) which protected the cultivated areas from the depredations of the nomadic tribes, and introduced improved agricultural practices such as the use of fallow, crop rotation, and organic manuring. Irrigation systems and aqueducts for the transport of water were constructed. Large states were established.

Periods of strong central government favoured sedentary cultivation. Law and order provided security from the invasions of the nomads, and made possible the execution of large-scale terracing in the hills and of irrigation projects in the valleys. Conscript labour or slave labour were probably used for these purposes.

The relative prosperity of agriculture does not necessarily mean that the lot of the cultivator was enviable. The social gulf between chieftains and their families on one hand, and of those who did the actual tilling of the soil on the other, was enormous; the former lived in mansions, the latter in hovels (Albright, 1956). Every weakening of the central authority was inevitably accompanied by incursions of the nomads, who at the best extracted tribute but more commonly pushed back the limits of the cultivated areas by ravage, plunder, and destruction. In the Maghreb, under the pressure of the nomads, many villages disappeared and cultivation became restricted to the mountain regions and the vicinity of the towns (Despois, 1961).

Slave labour has been abolished, but where farming is still practised in the arid regions by traditional methods – whether arable farming or nomadic herding – living standards are extremely low and life is difficult and hazardous to this day.

Desert pastoral agriculture

Nomadic livestock herding is still the most widespread form of land use by millions of people in the arid regions of North, West, and East Africa, the Middle East, and Southwest and Central Asia (Matlock, 1981).

The Near East and North Africa

In the arid areas of the Near East and North Africa, as well as on the land that is too steep or shallow or stony for cultivation in the semi-arid fringes of these areas, the sole traditional form of land use is grazing for livestock production. The stubble of cultivated crops also provides a welcome addition to the grazing areas in summer, when natural grazing has completely dried out (Fig. 8.3).



Fig. 8.3. Grazing the stubble: an important source of forage supply in most semi-arid regions. Photo Soil Conservation Service, Israel.

Sheep and goats predominate through the region; in the deserts there are also numerous camel flocks, whilst a small, hardy breed of dual-purpose cattle range the foothills and graze the stubble of cultivated crops and the spontaneous vegetation on fallow land in the areas of higher rainfall. Adjustment to varying degrees of aridity is achieved by various forms of seasonal movement of the stock.

In parts of North Africa, the flocks spend the summer months on the high mountain ranges and are brought down to the plains in winter. Stock movement may also occur according to the distribution and amount of rainfall – e.g., from the low-lying desert in winter, or to the maritime plains in summer.

In parts of Iraq, Jordan, and Syria, flocks of sheep and camels are completely nomadic and graze in the steppes, returning to cultivated areas only in years of exceptional drought. A form of semi-nomadism is also practised in the semi-desert parts of this region, the livestock being moved about over relatively short distances.

Whilst regular cultivation is alien to the mentality of the nomad pastoralist, the occasional sowing of patches of wheat or barley, in areas that have been wetted by a flash flood, or in low-lying lands to which he can divert some water by constructing a small dam on a wadi, is an important, if irregular, source of food supply.

In recent years, as a result of improved veterinary services and improved security conditions, the number of grazing animals has increased considerably, so that over-grazing has become even more accentuated than in the past. The better grazing lands

have also been taken under the plough, so that overstocking has led to deterioration of the remaining areas that are left available for grazing.

The combination of overstocking and variability in rainfall leads to considerable fluctuations in the numbers of livestock. For example in Algeria, a livestock population of 8 million head was built up during a succession of good years, to be reduced in 1945, after a few drought years, to 2 million (Droughin, 1962).

Western Eurasia and Central Asia

Nomadic herding has been the main form of land use from time immemorial in the deserts of Western Eurasia and Central Asia, where appropriate breeds of stock, mainly camels and sheep, were able to subsist on xerophytic and halophytic vegetation and on saline water unfit for human consumption (Kovda, 1961).

The most important plants of the cold desert pastures are such perennials as wormwoods (*Artemisia terrae-alba* and *A. herba-alba*) and *Salsola laricifolia*, which supply year-round grazing. In the southern, warmer parts of the Central Asian Desert, numerous winter and spring ephemerals predominate, which, after rains, provide large amounts of nutritious forage. The length of the grazing season depends largely on winter temperatures. In the coldest parts of the arid zone, animals have to be sheltered for 150–180 days each year, during which time they have to be fed with specially prepared forage reserves. This period is shortened to 80–90 days in Kazakhstan and Mongolia, and to only 30–40 days in the deserts of Central Asia.

The frequency of droughts and of fodder shortages varies considerably: from 10–20 years out of 100 on the semi-arid fringes of the area, to 50–70 years out of 100 in the fully desert zone.

In the drier parts of China, such as inner Mongolia, in which both the lack of rainfall and extreme temperatures are constraints to crop production, xerophytic vegetation enables nomadic pastoralism which has developed hardy breeds of Mongolian horse, cattle and sheep (Ren et al., 1985).

Transhumance is generally practised, with the animals moving to higher altitudes during the hot months, but descending into the flat desert plains and valleys during the colder months.

After centuries of haphazard grazing, much of the natural vegetation has deteriorated, as a result of over-use and of cutting for fuel. Dust storms are frequent and the movement of sand dunes is practically ubiquitous. Modern developments consist mainly of improved social and cultural amenities for the pastoral populations of the region, improved communications, and the establishment of a network of canals, wells, and borings. Central camps have been set up, with shelters and reserves of forage. Veterinary services are being provided, better breeds of stock are being developed, and wherever possible animal husbandry and arable cropping are being integrated on large collective and state farms.

The Indian subcontinent

The arid and semi-arid regions of the Indian subcontinent are the most densely populated regions in the world, with an average density of 61 persons/km², as compared to 3 persons/km² in other similar regions of the world (Mann and Dhir, 1984).

The pastoral system is the life style of the majority. Livestock considerably exceed the human population in numbers, and have had a significant role in degradation of the habitat. A rise in the sheep and goat population has increased erosion; unpalatable plant species have increased and useful plants destroyed by preventing their regeneration (Dakshini, 1985).

Sufficient fodder is one of the most important requirements, in view of the central role of animal production. It is estimated that the total forage from rangeland, top feed, crop residues, etc., is 12% below the total requirement.

Agricultural produce is also very limited, and entirely consumed within the area. Land allotments to marginal and submarginal farmers have caused damage to the environment. With low water supplies and scanty rainfall, crop production in these areas cannot be sustained for long, and the areas are generally abandoned after the ecological damage becomes practically irreversible (Dakshini, 1985).

In the predominantly pastoral society, the dependence of humans and their livestock on the scanty vegetational cover has become critical.

South Africa

The arid regions of South Africa comprise an area with predominantly winter precipitation – the Karoo – and an open savannah with predominantly summer precipitation. The name Karoo is derived from a Hottentot word signifying parched or desiccated (Talbot, 1961); it also designates the characteristic desert shrub vegetation of the region. In the savannah, grasses dominate, with scattered thorn-trees. These regions, despite their aridity, originally supported a fairly large and varied fauna of herbivores and the carnivores that preyed upon them. The native Bushmen subsisted on hunting, fishing, and food collecting, and were able to survive for fairly long periods in areas that were lacking in surface water.

In the 14th century, the pastoralist Hottentots moved into the area with their flocks (Shapera, 1936). Each tribe claimed as its territory the area in which it grazed its herds throughout the year; this was regarded as the inalienable communal property of the whole tribe (Talbot, 1961). Their cattle were of the Zebu type, and served as the parent stock from which the white settlers subsequently bred the modern Afrikaner cattle. The sheep were non-woolled, extremely hardy breeds, well adapted to grazing the range. The native goats were of very mixed stock – hardy, large-sized, and very prolific.

The arid interior was first used by white farmers for grazing after 1730. The great demand for meat arising out of the war between Britain and France, which brought

numerous warships and troop ships into Table Bay, as well as the increasing number of merchant ships travelling around the Cape, provided a practically unlimited market for fresh meat, and for the tail-fat, soap, and candles, derived from the sheep. With such economic incentives, livestock production expanded rapidly.

Land tenure was conferred on the basis of periodically renewed grazing licences for vaguely defined areas. This favoured nomadism, and the graziers would move to new pastures whenever the need arose. At a later stage, grazing rights referred to specified localities, which could be identified – usually by the farm buildings and corrals of the homestead. An individual holding would comprise the area within the radius of half-an-hour's walk from the farmhouse. Homesteads were established wherever water made permanent settlements possible.

The Hottentot flocks were completely displaced from the range; many of the Hottentots themselves were employed by the whites as herdsmen, shepherds, wagon drivers, etc., so that land use of the range continued to be based mainly on the experience and traditions of the Hottentots.

Transhumance was generally practised. After the winter rains, abundant and nutritious annuals appear, and the grazing is sufficiently succulent to enable the stock to subsist in areas without surface water. In summer, large areas in the region of summer rainfall, called the 'trekveld', served for grazing on a communal basis, after summer rainstorms had filled the water pools. The movements of the stock were generally parallel to those of the game, so that the summer trek of the graziers provided not only fresh pastures but also new hunting grounds. The regular seasonal movements of the stock were frequently upset by drought, invasions of Brown Locust (*Locustana pardalina*), and the appearance of enormous herds of migratory Springbok (*Antidorcas marsupialis*), which together could completely destroy the grazing. When this occurred, the graziers had no choice but to search for alternative grazing areas. Both seasonal and emergency migrations were an essential element of the land use of the area.

Towards the end of the 18th century, Merino sheep were introduced into the Cape. By cross-breeding with selected Cape sheep, a dual-purpose Merino-type sheep was evolved, which was a better meat producer than the Cape sheep and at the same time produced high-quality wool. In the middle of the 18th century, some fat-rumped Hedjaz sheep were introduced, from which, by selective breeding, a distinctive South African breed was developed – the Blackhead Persian. This breed is extremely hardy and disease resistant, relatively prolific, and well adapted to grazing under arid conditions. In 1909, Karakuls were introduced, which are raised for the pelts of their unborn and new-born lambs. The fact that the ewes do not have to nurse their young, gives them an advantage over other breeds of sheep, so that Karakuls can thrive where other breeds would starve.

Goats played a complementary role to sheep, as they could graze on vegetation that was unsuitable for or inaccessible to sheep.

In addition to the traditional farm animals, an original source of income was

provided by ostrich farming in the Karoo. At first, the prime feathers were the main product; subsequently, feathers for dusters, ostrich-skin leather, and ostrich biltong, found a ready market. Ostrich raising also provided the first impetus for irrigating small areas of the desert. Because of the need to provide an adequate source of proteins for the birds, lucerne (alfalfa) was grown under irrigation as a supplement to the natural range.

The Kalahari Desert was opened to settlement after the First World War, with the Government establishing bore holes before allocating any usable land to the settlers. The grazing was found to be better suited to cattle; sheep suffered from internal parasites, diseases, and depredations by jackals. However, cattle also failed to thrive, and suffered from a disease called 'lamsiekte'. Only as late as 1919 was it shown that this disease was due to a deficiency of phosphate, reflecting the extremely low phosphate content of the soils. After this problem had been overcome by a supply of bone-meal or phosphate licks, cattle ranching, based mainly on Afrikaner stock, was able to develop. This took two forms: (a) a fairly primitive form of combined beef and dairy production, whereby the calves were kept kraaled, whilst the cows grazed the range within a limited radius; and (b) extensive beef ranches, on units of 4000 ha and more. Beef production was a far more rational form of land use than the primitive dairy ranching. The steers required less water and less labour, could graze much farther from water, and could make better use of the feed.

Range improvement and deterioration

The first and major improvement to be adopted was the fencing of the grazing land into paddocks, each with a drinking place. This made possible rational pasture management, which increased carrying capacity by at least 30% during normal years. By periodic resting of parts of the veld, reserves of forage were established, to be used during drought years. The need for transhumance was reduced, and seasonal trekking became the exception. Fencing also helped to prevent the spread of stock diseases, and made continuous herding by day and kraaling by night unnecessary.

Locusts, migrating Springbok, and predatory carnivores such as jackals and leopards, were brought under control. The improved conditions made it possible to increase the overall number of sheep and to replace many of the hardier Afrikaner and Blackhead Persian sheep by the more remunerative wool-producing Merino and, to a lesser degree, mutton-and-wool crossbreeds. These possibilities were, however, not always fully exploited, and land use was not always judicious: large areas of veld deteriorated as a result of overgrazing, as stocking rates were frequently based on the carrying capacity of good years. The decline of trekking brought in its wake increased pressure on grazing lands, on which rational grazing was not effectively carried out. Perennial grasses disappeared and were largely replaced by toxic and unpalatable species. The most harmful has been the spread of non-palatable Karoo into the sweet grassveld, probably as the result of overgrazing (Bowden, 1979). Run-off and soil erosion increased as a result of the reduced plant cover and exposed soil.

The introduction of exotic plants such as the Prickly-pear (*Opuntia megacantha*) and Jointed Cactus (*O. aurantiaca*), which spread rapidly over enormous areas, was extremely destructive to grazing, and also caused the death by poisoning of thousands of animals annually. After many costly efforts, these cacti were brought under effective control by a combination of mechanical, biological, and chemical, methods (King, 1966).

Nevertheless, as a result of these various vicissitudes, most of the original vegetation of the range has changed considerably – usually for the worse, the deterioration being most marked in the more arid parts.

The American desert

The first advent of the White Man, in the middle of the 18th century, in this region was mainly concerned either with missionary activities or with the search for gold, and had little direct impact on land use (Armillas, 1956). But in the second half of the 19th century, there began an influx of settlers from the east, mainly graziers. This was the era of the ‘open range’, a settler would lay a claim to a watering place, and thereby have effective control over vast areas of adjacent grazing lands.

Conservation methods were practically unknown; nor did the ranchers, lacking legal rights to the range, have any incentive to make basic improvements on their holdings. The first procedures for establishing title to the lands, and the system of land division itself, were based on those prevalent in the humid areas of the United States, without regard to the differences in climate, water resources, soil type, and topography. As a result, land was allotted without any appraisal of its potentialities, and the size of the allocations remained constant whatever the potential productive capacity of the land; the country was also divided into rectangular holdings without concern for erosion problems. Misuse and overstocking reduced the carrying capacity of the range by over 50% in the course of several decades (Logan, 1961).

It was only in 1934, during the periods of droughts and depression, that an Act was passed to change this situation. A land-classification authority was established, and the grazing land was brought under the control and management of the federal government.

Under the primitive and rigorous conditions prevailing on the range, only a very hardy breed of cattle, capable of travelling large distances and requiring a minimum of water, could exist. The typical breed of the period, adapted to these conditions, was the Texas Longhorn – whose productivity, however, was low.

Though the ranches were usually based on a reliable water supply, the sparse vegetation made it necessary to graze huge expanses of land with widely spaced waterholes, so that the cattlemen actually led a semi-nomadic existence. A form of transhumance was also practised, with the animals grazing in the valley bottoms in winter and on the higher mountain areas in summer.

On the range, sheep have certain disadvantages over cattle. They tend to uproot

the grass, thereby denuding the range and increasing the hazards of erosion. They pasture in compact flocks, trampling everything in their path, doing more damage with their small hooves to young seedlings than caused by the larger hooves of the cattle. On the other hand, sheep are better adapted to the sparse vegetation of the desert range.

Sheep and cattle are not incompatible, and can graze the same range, as is the practice in the Utah desert range. However, on the whole, cattle production is predominant on the American range; this may be due largely to the preference of the American consumer for beef rather than mutton.

The conflict between grazing and farming

It is interesting to note that the traditional conflict between the pastoralist and the crop farmer, characterizing the dry regions of the Old World, was repeated in the drylands of North America in the 19th century.

Homesteaders were required to clear for cultivation and grow a crop on at least part of their land in order to obtain a legal title to it. In order to keep out the cattle, the land had to be fenced. This, in many cases, prevented free access of the cattle to water, and thereby made large areas of adjacent range virtually unusable. It was only after a long period of bitter conflict that stockmen and farmers found that their production could be complementary – that the development of the full potentialities of the range, with its unreliable and fluctuating forage supply, was dependent on a balancing source of animal fodder, which in turn required assured reserves of forage. Forage reserves, in the form of hay or silage, were usually produced under irrigation. Thus stock production on a high level was dependent on the integration of animal husbandry and forage production.

Whilst irrigated agriculture was highly successful in the desert areas, attempts at dry-farming, based on the methods developed in more humid regions, generally ended in failure. Occasionally, the sowing of dryland crops of grain coincided with years of more or less adequate rainfall; this encouraged putting larger areas under the plough. The results, in the long run, were not only financially disastrous; this practice also destroyed, sometimes permanently, the native vegetation and laid the land bare to erosion by wind and rain.

The production of forage reserves under irrigation made it possible to reduce the areas required by the individual rancher, and also to fence the range. Thereafter, the rancher had the incentive to conserve and even improve his holdings. The extension of the railways made the long drives to the markets unnecessary. An assured forage supply, improved range, and smaller distances to be covered by the cattle, made it possible to replace the Longhorn by less hardy but more productive breeds, which produced a higher quality of meat. The Hereford from Britain became the dominant breed of the range; at a later stage a new breed, the Santa Gertrudis, was produced from a cross between a Zebu-type animal from India with the British Shorthorn, to withstand heat and fly-borne tropical diseases. Technological improvements were

also introduced into the range: windmills, well pumps, water-storage tanks, and pipelines, improved the supply of water; scientific range management replaced overgrazing while improved veterinary techniques, better-bred animals, and supplementary feeding, increased productivity and quality. It became possible to replace migratory herding by different forms of controlled grazing. Where transhumance continued to be practised, the cattle were transported by trucks from the winter to the summer range and vice versa.

A family-sized ranch requires at least 150 head to maintain an acceptable standard of living according to American standards. The average size of a ranch in the American desert regions is about 8000 ha (Logan, 1961). Most of the land is leased from the Government; the fees paid by the rancher are usually invested by the Government in improving the range.

Three types of ranching economies are practised on the desert ranges: (a) young steers are purchased outside the ranch, to be raised on natural grazing until they achieve the most economic weight; (b) a calf crop is produced on the ranch, to be sold shortly after weaning; and (c) two-year-old steers are raised on the ranch (or older steers, according to the type of range).

Arid Australia

Three-quarters of Australia is arid, of which about half is unpopulated desert. The other half is mainly used for grazing cattle for beef and sheep for wool (Perry and Graetz, 1979).

The aboriginal population of the arid areas of Australia was extremely sparse. They were nomadic and lived from hunting and food gathering only, making no attempt to cultivate plants or to domesticate animals; therefore they had no disturbing influence on plant cover and did not cause degradation of the soil, as was the case in other regions (Wadham, 1961).

White settlement in the dry interior started around 1820 and was prompted by the excellent market in Britain for Australian wool, produced in the humid coastal strip. The first attempts at sheep raising in the dry region were generally unsuccessful; it was only far later that it was demonstrated that the basic reasons for these failures were the low phosphorus content of the soils and, in certain cases, the lack of specific trace elements. However, occupation developed rapidly as watering points were established and areas fenced.

Within a relatively short period most of the accessible areas were being used for sheep grazing. Cattle were better adapted to the arid range than were sheep, mainly because they could graze in a far greater radius around the watering points, but they were economically far inferior: markets for beef were limited and the other principal products, hides and tallow, could not compare with wool in economic value.

Towards the end of the 19th century, two developments occurred which had a

far-reaching effect on land use in the arid areas of Australia: (a) a large number of bores were developed, many of them free-flowing and others requiring pumping, which supplied semi-saline water for the stock and made possible a considerable increase in the intensity of stocking; and (b) there was an epidemic spread of rabbits, which competed with the stock for the available grazing. As a result of both these developments, overgrazing caused the pastures to deteriorate rapidly.

As in all desert areas, there were great annual fluctuations in production, due to recurrent droughts; considerable fluctuations in the price of wool also created conditions of economic instability.

In Australia, as elsewhere, the legalizing of individual claims to the grazing areas was followed by fencing, improvement of water supplies, construction of buildings, and attempts to improve pasture management.

The size of the individual holding was based on the principle that the landowner should be assured of an income roughly comparable to the basic wages prevailing in the cities. However, estimates based on the price of wool, with its considerable fluctuations, could not be very accurate or lasting. In the 1930's, the number of sheep estimated as necessary for a satisfactory family income was set at 3000; the grazing area required for an efficient farm unit varied from 1200 ha in southwestern New South Wales, to 20 000 ha in the more arid areas situated farther north in New South Wales.

Earlier, a number of economic setbacks had occurred, due to the epidemic spread of sheep diseases and pests, to droughts, to price fluctuations of wool, and to the depredations of rabbits. These had culminated in a near-catastrophe in 1891, when several successive years of drought, which caused the death of 50 million sheep coincided with a sharp drop in the price of wool and a worldwide financial crisis. Sheep populations declined by 35 to 60%, according to the region, with the more arid areas incurring the greatest losses. Recovery was gradual, but the flock population never again attained the levels reached before 1891.

Grazing in Australia is pushed farther beyond the dry side of the 250 mm isohyet than in America. Grazing density of the 'sparselands' of Western Australia is about one cow per 160 ha, whilst in Arizona, ranges with less carrying capacity than one cow per 20 ha, are not in use (McDonald, 1959).

In Australia, nomadic land use does not exist (Christian, 1964). There is some movement of stock during drought periods to less affected pasture areas, and also movement of stock from breeding to fattening areas – the nearest approach to nomadic grazing. Stock routes over which the herds travel are provided with water bores, at distances of from one to two days travel.

Perry and Graetz (1979) conclude their review of land use in arid Australia with the statement that the financial costs and returns of technological innovations such as plant introduction or grazing and harvesting of exotic animals effectively preclude their adoption. Because Australia is fortunate in not needing her arid lands to feed her population, it is not necessary to overexploit them. With a small capital invest-

ment it is possible to obtain a good financial return from the production of livestock products for export.

Potentials for intensification of desert agriculture

In the regions in which rainfall is not usually adequate for the production of conventional crops, the following measures can be adopted as a means of intensifying agricultural production:

- (a) Supplying additional water, either through water harvesting and spreading, tapping surface or underground water resources in the region or by transfer of water from outside the region. These options will be discussed under 'irrigation agriculture' (see p. 377).
- (b) Commercial exploitation of plants adapted to desert conditions.
- (c) A more rational and scientific approach to the traditional use of desert areas for livestock production.

Economic plants of the desert

Desert plants used by desert inhabitants. Since time immemorial, desert plants have supplied many needs of the local human inhabitants. Foods and spices, fibres, medicines and drugs, shelter materials, and weapons, are obtained from a large variety of desert plants.

Dakshini (1985) points out that the native plants not only provide food and fodder; each of the 1600 plant species found in these regions has some economic value, and all have become an essential component of the lifestyle of the inhabitants of these harsh environments.

An interesting example is the use of dried branches of *Alhagi pseudoalhagi* and *Calligonum polygonoides* to form screens that, after wetting, cool their homes when hot, dry winds make life difficult. This is essentially the same technique used in modern agriculture to cool greenhouses during the hot months.

Fruits. The *Opuntia* and *Agave* spp. are the principal fruit producers of the North American deserts (Burgess, 1965). The succulent Euphorbias of the African deserts, however, contain large amounts of very toxic alkaloids. Berries of many species are additional sources of nutrition.

Starch-filled storage organs. Edible roots, rhizomes, tubers, bulbs, etc., are also found in a large variety of desert plants. The 'hearts' or tender, inner parts of many species (e.g., *Agave*, *Yucca*, etc.), after roasting, serve as a staple food of many American Indian tribes.

Seeds and nuts. Seeds and nuts, legume pods and acorns, are important food-sources. The seeds of many of the annual species – grasses, composites, legumes, chenopods, mustards, and others – are gathered and used fresh, dried, parched, or ground. Some plants, such as various *Prosopis* species, produce an abundance of large and nutritious seeds (Burgess, 1965).

Greens and herbs. The young shoots or leaves of many desert plants are used as salads or condiments.

Drugs and medicines. Many desert plants have biochemical constituents that have a therapeutic value or serve as narcotic drugs or stimulants, etc. Dried or ground parts of the plant, as well as decoctions, have traditionally been used for these purposes.

Fibres. Many desert plants supply fibres that have a wide variety of uses; *Yucca* and *Agave* are the principal genera involved (Bender, 1963).

Miscellaneous uses. In addition to the above, desert plants supply building materials, weapons, tools, ornaments, dyes, gums, fuel, soap, perfumes, etc.

Desert plants of potential commercial significance for arid growing conditions. The potentially most interesting arid-zone plants are those which contain constituents whose manufacture by the plant is not adversely affected by aridity or may even benefit from dry growing conditions, and whose commercial value per unit weight is very high. Plants containing alkaloids, essential oils, and mucilaginous materials, clearly belong to this category.

Plant species producing constituents of economic value, but whose yield is proportional to the vegetative growth of the plant – such as fibres or food reserves – and have a relatively low intrinsic commercial value, are, a priori, less promising.

The number of desert plants containing *alkaloids* are relatively few, but their alkaloid content can be very high (Paris and Dillemann, 1960), with members of the Solanaceae commonly the richest source. Thus the most important alkaloids of desert plants are the hyoscine and hyoscyamine groups found in *Datura inoxia* and *D. stramonium*, *Hyoscyamus muticus* and *H. albus*, and *Physochlaina praelata*, while steroidal alkaloids have been isolated from various species of *Solanum*, e.g., *S. carolinense* and *S. xanthocarpum*. Ephedrine is contained in a few species of *Ephedra*, and a variety of other alkaloids, too numerous to mention, are found in other desert plants (Chopra et al., 1960).

The second important group of constituents contained in many desert plants consists of *essential oils*; the secretion of essential oils appears to be a xerophytic character conferring a degree of protection against drought (Fluck, 1955). The main sources are plants of the families Labiatae: *Salvia officinalis*, *Lavandula officinalis*, *L. latifolia*, *Rosmarinus officinalis*; and Umbelliferae: *Foeniculum vulgare*, *Pimpinella anisum*, *Ferula alliacea*, *F. assafoetida*, *F. foetida*, and *F. galbaniflua* (Chopra et al., 1960). Other important sources of aromatic oils are members of the genus *Artemisia* (Compositae).

The third group is composed of the mucilaginous plants, producing medicinal *gums*, which are contained in various species of *Acacia* and in *Butea monosperma* (Leguminosae). The mucilage plays a part in water retention and is therefore an important xerophytic character; it has also been established that gum production is favoured by low atmospheric and soil humidity (Paris and Dilleman, 1960).

A fourth group consists of rubber-bearing plants, such as *Guayule* and of crops that can produce hydrocarbons of lower molecular weight than rubber and can serve as fuels, such as *Euphorbia* spp. (Hall, 1981).

Stipa tenacissima (Gramineae) is collected in North Africa for the production of paper pulp.

Thymelaea hirsuta is a perennial shrub that covers vast uncultivated desert areas along the Mediterranean coasts of Egypt, that has been recommended for the production of paper pulp (El Ghonemy et al., 1979).

Examples of desert plants used commercially. Various species of *Hyoscyamus* are specific to certain desert areas. Thus *H. muticus* is indigenous to Egypt, the Near East, Arabia, Iran, and India. It is the only wild plant in the Egyptian Desert that is of sufficient commercial value to justify its export (Drar, 1954). Attempts to cultivate *H. muticus* in various countries other than Egypt have not met with success (Chopra et al., 1960). Even in Egypt, the plants under cultivation had a lower alkaloid content than those growing wild, while the percentage of alkaloids was greatest in plants growing under the most arid conditions (Paris and Dillemann, 1960).

Citrullus colocynthis (Cucurbitaceae) is native to Arabia, Syria, Egypt, and India. The pulp of the unripe fruit yields the commercial drug colocynth, which is used as a cathartic. *C. colocynthis* used to be collected and exported in large quantities from Egypt; it is grown in Cyprus and Spain (Chopra et al., 1960).

Ephedra (Gnetales) species are found mostly in the arid regions of the temperate zone. The dried young branches are a source of the alkaloid ephedrine, which has an action similar to that of adrenalin. *Ephedra* species have been cultivated successfully in the USA, England, Kenya, and Australia (Chopra et al., 1960).

Various species of *Agave* (Amaryllidaceae) are being grown for their sapogenins in Italy, Sicily, and Malta (Chopra et al., 1960). One species, *A. roseana*, yields 2.5% by dry weight of hecogenin, a steroidal sapogenin which is a precursor of cortisone and other steroidal hormones. Another species, *A. sisalana*, has been grown commercially on a large scale in East Africa and India, for the production of fibres for the sisal industry. Agaves are extensively cultivated for fibres in the Pueblo Desert of Mexico (Chopra et al., 1960), but attempts to grow *Agave sisalana* in the arid parts of Israel (200–250 mm rainfall) have not been economically successful.

Yucca (Liliaceae) is one of the genera with the greatest abundance of steroid saponosides. Its species are plants of the desert and semi-desert regions of Mexico and the south-western United States, and are exploited commercially for their long textile fibres; after extraction of the fibres, the residue serves as a source of saponosides. The plants are extremely slow-growing, and long periods must elapse before it is possible to return to 'harvested' areas (Paris and Dillemann, 1960).

Aloe (Liliaceae) is a genus of xerophytic plants that are indigenous to East and South Africa. Aloes can be grown on very poor soils. The concentrated juice provides the drug aloes, which is a mixture of glucosides and is largely used as a cathartic. Some species are grown as a crop in South Africa, Arabia, and India (Chopra et al.,

1960), while *Aloe vera* is cultivated in the Dominican Republic, along the Venezuelan coast, and on the island of Aruba – all for the commercial production of the drug aloes (Paris and Dillemann, 1960).

Artemisia (Compositae) species are abundant in arid regions of the Asiatic steppes and in the western United States, South Africa, and South America (Chopra et al., 1960). Santonin-bearing *Artemisia* species (mainly *A. cina*) are being grown in Russian and Iranian Turkestan. So far, attempts to grow *A. cina* outside these regions have not been successful (Paris and Dillemann, 1960). The santonin is an anthelmintic. *A. herba-alba* is widespread in North African deserts. Though it contains no santonin it has vermifuge properties. These plants are collected and marketed as Barbary santonica (ibid.).

Wormwood (*Artemisia absinthium*), a native of northern Asia and Afghanistan, is cultivated in the United States. The essential oil extracted from it has a tonic and stimulating effect on the digestive organs (Chopra et al., 1960).

Canaigre (*Rumex hymenosepalus*) occurs in the arid regions of Mexico and the USA, where wild stands were used as a source of tannin (Bender, 1963). After these stands had been depleted, attempts were made to grow canaigre as a commercial crop, but it could not compete economically in the long run with other sources of tannin.

Protein and oil contents of desert plants. The seeds of many species of desert plants have been found to have above-average protein and oil contents, while some species contain oils of unusual fatty-acid composition (Bender, 1963). Of these, *Lesquerella fendleri*, indigenous to semi-arid North America, has seeds with an oil content ranging from 20 to 40%, and the oil has potential industrial uses.

Prospects of commercial exploitation of desert plants. Harvesting from natural stands. The natural stands of most potentially valuable desert plants are too diffuse to permit harvesting to be economical, except possibly for people with a very low standard of living. Even plants of medicinal value that are relatively abundant in the desert may encounter difficulties when it comes to marketing, due to competition from cheaper sources. In other cases, the plants are not sufficiently abundant to provide an adequate and continuous supply. In the few cases of a seemingly abundant supply, such as that of Candelilla (*Euphorbia antisyphilitica*) plants (for wax) in Mexico, and *Hyoperimus* in Egypt, which is collected for its alkaloid constituent (Drar, 1954), excessive harvesting has rapidly led to a depletion of the natural populations.

Candelilla (*Euphorbia antisyphilitica*) grows in the sandy areas of the Chihuahuan Desert. The plants are drought and salinity resistant. They have been collected for many years as a source of candelilla wax, which has a great variety of industrial uses (Bender, 1963). The economics of collection and extraction are marginal (McKell, 1985).

Ixtle is the generic name for hard fibres obtained from *Agave lecheguilla* and *Yucca*

carnerrosana. These plants represent one of the principal sources of employment in the Chihuahuan Desert of Mexico (Hall, 1981).

Inevitably, excessive exploitation of natural stands will lead to their extermination; hence the need for some practical control measures to ensure sustained harvesting.

Domestication of desert plants

The early efforts. Serious domestication efforts, involving a very large investment in plant breeding, management practices and methods of processing, were undertaken on a number of desert plants of potential economic value, beginning in the early 1940's.

Examples of these early efforts are domestication of canaigre (*Rumex hymenosepalus*) for tanning, agave (*Agave* spp.) for fibre, guayule (*Parthenium argentatum*), and kok-saghys (*Taraxacum kok-saghys*) for rubber, and jojoba (*Simmondsia chinensis*) as a potential source of liquid wax.

Guayule (*Parthenium argentatum*) is a small Mexican semi-desert shrub, containing 10–18% of high-quality latex in its leaves, stems and roots, virtually identical in chemical and physical properties to Hevea rubber. In its native habitat, guayule may live 30 years or more. It occurs at elevations between 600 and 2000 m in semi-desert drylands of Mexico and Texas, with a summer rainfall of 200–375 mm. Under cultivation, it has been successfully grown in regions of winter rainfall of 350 mm. Supplementary irrigation has generally been necessary where rainfall is less than 350 mm (McGinnies, 1979).

When supplies of natural rubber from Southeast Asia became unavailable to the USA in the course of World War II, a tremendous scientific investment was devoted to domestication of guayule as part of the war effort. The entire project was aborted at the end of the war.

Jojoba (*Simmondsia chinensis*) is a native plant on the Sonora Desert. It grows in native stands with less than 120 mm of rainfall per year, and is also quite resistant to salinity.

The plant can serve as a potential source of liquid wax, a possible substitute for sperm whale oil, especially important since the sperm whale has been placed on the endangered species list.

Yermanos (1979) summarizes the advantages of jojoba as follows: the seed contains a liquid wax which can serve as a replacement for sperm whale oil; the plant is extremely drought resistant and can grow in areas of marginal soil fertility, high temperatures, high salinity. Fertilizer and energy requirements are low. The crop can be processed with commercially available equipment. Yermanos concludes that jojoba "appears to have potential in several semi-arid areas around the world with high population density and limited employment opportunities, where little else can be grown".

Because of the diffuse nature of native jojoba stands, harvesting from the wild is uneconomical. Since the 1960's a considerable effort has gone into the breeding,

cultivation, and processing of jojoba (Goodin and Northington, 1985). High prices for the oil and waxes for the lucrative cosmetics industry, led to the commercial production of jojoba on a large scale in California, Arizona, the Middle East, Africa, South America and Australia. A few of these plantations came into production in the mid-80's (about five years after planting).

Most of the investors expected the crop to be drought resistant, with exceptional production ability on desert soils with little water or fertilizer. Though the plant is highly drought resistant, good yields however require 380 to 500 mm of rainfall. Under cultivation, the plants are susceptible to *Phytophthora* and *Pythium* diseases. Harvesting by hand is very expensive. The market for the crop appears to be quite uncertain (Goodin and Northington, 1985).

Potentials for economic exploitation of desert plants. The early efforts at economic exploitation of desert plants were on the whole, disappointing. As mentioned above, natural stands of potentially valuable plants were too diffuse to be economically harvested. Commercial production in the truly arid conditions that are characteristic of the native habitat of the plants concerned has usually failed to be economical. It is probably unrealistic to expect commercial cultivation in areas with less than 200 mm of annual rainfall.

If the desert plants are grown under more favourable conditions of precipitation, and still more so if they are irrigated, the content of the valuable constituents is markedly reduced in most cases. This is not surprising in view of the fact that the production of these constituents by the plant is often a protective measure against aridity.

Up to the present, success in a few limited cases, such as the cultivation of guayule, has been dependent on war-time shortages or other special economic considerations – such as the desire to be independent of outside sources, which has led to the extensive cultivation of the rubber-producing kok-saghys (*Tarascacum kok-saghys*) in the former USSR. When once the situation returns to normal, however, cultivation has usually ceased.

Whaly (1952) summed up the situation by stating that: "The potentialities of the world's flora seem sufficiently well known to enable the conclusion to be drawn that the likelihood of finding crops of economic significance that can be grown commercially on a large scale in the arid regions, without irrigation, is only slight." Whatever specific advantage plants that are native to arid lands may have, these are attenuated when the plants are grown under irrigation. With an assured water supply, there is a great choice of mesophytic crops, with high-yielding potentialities and commercial value; the native desert plants can rarely compete under these conditions.

More recently, interest in the commercial utilization of dryland plants has been rekindled. Hall (1981) warns against the tendency to extrapolate previous experiences to present-day circumstances, without understanding all the factors that influenced prior schemes and others which might contribute to the success of new pro-

jects. Botanical, ecological, economic, social and political factors can change in the course of a decade.

The National Academy of Science of the US, in the early 1970's, set up a committee to investigate the possibilities of introducing and domesticating new crops. Their findings were published in 1975 (NAS, 1975) and have done much to publicize, worldwide, the possibilities of domesticating new crops.

In the course of the 1980's, considerable research effort, both nationally and internationally, has been invested in the study of the potential value of native plants of the arid and semi-arid tropics.

In contrast to the negative conclusions drawn from the early efforts at utilization and domestication of unconventional plants from the world's drylands, many recent authors are very optimistic. Bell (1985) states that fewer than 1% of the world's plants have been sufficiently well studied for a true evaluation of the potential plant wealth awaiting discovery.

Timmermann and Hoffmann (1985) write in the same vein: "In practical terms, the arid and semi-arid lands of the world are vast and underutilized, and the development of native crops as renewable sources of speciality chemicals and other commodities that could be grown in these regions would be an accomplishment of considerable economic importance. Moreover, crops of this type would not compete with conventional food and fibre crops that require more productive land".

Even the possibilities for indigenous natural rubber production is being seriously re-examined in Mexico, the USA, and other countries (Hall, 1981).

Considerable interest in guayule was rekindled in the wake of the 1973 oil embargo, when the US realized the importance of being able to produce strategic national supplies of certain commodities, even when not justified by strictly economic criteria. This interest subsequently spread to most arid parts of the world. The success of guayule as a domestic crop will probably depend on government subsidies, justified because it is an important strategic resource.

Nabhan and Felger (1985) note that "arid lands worldwide offer a rich variety of wild and indigenous cultivated food plants adapted to low and variable precipitation regimes". The arid lands of the New World are especially rich in succulents with fructose-rich fruits, perennials with large starch-rich tuberous roots, annuals with protein and oil-rich seeds.

In the Sonora Desert alone, about 20% of the vascular flora are food plants (some 450 in number). From this inventory, the authors have described selected examples of species endowed with superior adaptations to arid conditions, economic products, and adaptability to cultivation. Many of these plants are locally utilized, and commercially marketed, and some even exported. These include species of *Agave*, *Cap-sicum*, *Ceiba*, *Cnidoscolus*, *Cucurbita*, *Lycium*, *Opuntia*, and *Phaseolus*.

Further development of potentially useful plants can be enhanced by hybridization and innovative selection techniques. Many of these plants can also serve as genetic sources of resistance to drought, heat, and salinity for related cultivated species.

In a study of food plants of the arid and semi-arid areas in Namibia, Arnold et al. (1985) conclude that five species: *Cucumis metuliferus*, *C. africanus*, *Tylosema esculentum*, *Pelargonium incrassatum* and *Coccinia sessilifolia* are important candidates for domestication.

Amaranthus, a native to Central and South America, is now cultivated on a wide scale in India. In some areas *A. hypochondriacus* constitutes a staple food in place of bread wheat. The amaranths are a potentially important crop for arid regions because they are C4 plants, that grow rapidly in hot weather, and have a relatively low water requirement. Their high lysine content makes them especially useful for countries where protein deficiencies are a major nutritional problem (Khoshoo and Subrahmanyam, 1985).

Le Houérou (1985) reviews some 160 species of potential economic value as fodder or fuel in North Africa, the Near and Middle East, with a view to their possible use in revegetation programmes. Among the species studied, there are a number that "make it possible to meet virtually all possible ecological conditions within the region, in terms of climates and soils".

Efforts are being made in California to establish trial plantations of crops which produce hydrocarbons of lower molecular weight than rubber, as a source of liquids with properties very close to those of petroleum (Newton and Goodin, 1985). *Euphorbia* spp. are being investigated for this purpose, with a potential of producing about 20 barrels of "oil" equivalent per ha per year in a desert-type environment. In Brazil, trees (*Cobafeira* spp., *Croton* spp.) have been identified which produce "oils" that can be used directly, or after processing, in engines (Hall, 1981).

Timmermann and Hoffmann (1985) are more pessimistic regarding the short-term potential of producing liquid fuels, which presently appear to be uneconomical in view of the decreased prices of petroleum; they suggest that a more feasible approach for the near future would be the development of new crops that provide chemical commodities that are considerably more valuable than crude oil. *Grindelia* is considered as a promising candidate for this purpose.

In a wide-ranging review of non-agricultural plants of arid lands in India, Khoshoo and Subrahmanyam (1985) give examples of desert plants which have been fully researched regarding their utilization as food plants, multipurpose trees, and medicinal and industrial plants, and present details on the socio-economic potential, cultivation practices and future research needs to develop these potential crops. To cite a single example: the authors state that the neem tree (*Azadirachta indica*) "has great potential because of its multiple uses as firewood, timber, and in pharmaceutical and pesticide preparations; it holds great scope for developing village industries, generating employment and thus boosting the economy". They further indicate that almost every part of the tree, from its roots, trunk, bark, leaves, flowers, fruits and seeds is known to have some use.

Plants for saline areas. Aronson (1985) suggests that halophytes could provide the best potential for forage production in the many saline parts of the dry regions.

Newton and Goodin (1985) consider plants of the genus *Atriplex* (saltbushes) to have the greatest potential for forage production with sustainable productivity, at a rate of conversion of the intensive solar energy available in the dry areas which would be sufficient to justify the cost.

Because of the ability of the saltbushes to survive and produce exceptionally large quantities of biomass under extremely saline conditions, and their high nutritional value, the rate of development research on *Atriplex* and related shrubs has accelerated and spread to various countries. The seeds of these plants have salt levels below 10% by dry weight, and a nutritional value that is generally as high or higher than that of conventional oilseeds (Aronson, 1985).

Other important halophytes in the genera in the family of Chenopodiaceae are *Chenopodium*, *Kochia*, *Maireana*, *Salicornia*, *Salsola*, and *Suaeda* (Aronson, 1985).

Halophytes are also increasingly used for reclamation of saline lands. In the hypersaline Lago Texcoco near Mexico City, the saltgrass *Distichlis spicata* is successfully grown and has stabilized 6000 ha of lake bed; the grass is irrigated with city sewage (Aronson, 1985).

Arons (1985), from his global review of economic halophytes, concludes that their increased utilization in arid and semi-arid areas in the very near future seems very likely. He points out that escalating problems of desertification and salinization, and the inability to provide sufficient water of the quality required by conventional crops, justifies his conclusion.

Potentials for improving range and livestock productivity

The Dryland Agriculture Technical Committee (1979) mentions the following interwoven complex problems faced by rangeland–animal systems in developing dryland areas, in order to be improved:

- heterogeneous climates and soils;
- deteriorated rangelands, whose condition is worsening rapidly;
- lack of reserves of forage and the necessary infrastructure;
- transportation problems for marketing animals;
- no facilities for storing meat;
- emphasis on numbers of animals, without regard to quality or effect on the rangelands;
- poorly defined property rights, both for land and for animals.

The low and uncertain rainfall and low productive potential of the dry rangelands, whether savannah or steppe, set severe limits to the possibilities of intensification, and the acceptable level of capital investment (Barnes, 1979).

Strategies for rangeland use

Box (1981) has reviewed and compared the strategies adopted by a number of representative countries in the use of their rangelands. The following is a brief summary of his analysis. In Table 8.1 the major characteristics of these countries relevant to a choice of strategy are indicated.

In the USA, with 94% of the population living in an urban setting, the major demand from rangelands is no longer animal products, but more recreation, wildlife, open spaces – in brief, quality of life. Conservation has become more important than exploitation.

In Australia, the major concern is economic yield and development. Range management is extensive, with low inputs of labour. Capital is invested only at times of high prices for animal products. Exploitation, rather than conservation is the ‘leitmotiv’.

In East Africa, the major input is labour; production is exploitative in dry years and inefficient in years with sufficient rainfall, resulting in a subsistence economy. The system is fairly stable, as long as pressure on the range is not excessive.

In the People’s Republic of China, a centralized government control places excessive demands on the range; the policy of increasing animal numbers above the carrying capacity of the range has led to widespread desertification on the steppes and desert fringes of China.

Most rangelands in the dry regions fall into one of the categories described above, with similar implications.

TABLE 8.1

Major characteristics in relation to rangeland policy

Country	Economy	Land	Labour	Capital	Management
USA	industrialized, highly advanced	limited	limited	adequate	adequate
Australia	non-industrialized, highly advanced	plentiful	scarce	scarce	adequate
East Africa	agrarian, developing, free enterprise	limited	ample	scarce	lacking
China	agrarian, developing, centralized	limited	ample	scarce	lacking

Improving productivity of the range

Proper management of the dryland grazing areas consists of two major elements, which are, of necessity, largely complementary: (a) proper grazing management; and (b) improved productivity of the range.

The cost of adopting a package of improved practices may be very high, but the potential benefits are also very high and may result in increasing production of the range by 100 to 1000% (Herbal et al., 1977).

Grazing management. The major characteristics of dry area rangelands are variability and unpredictability of the factors with which management must contend. Different types of vegetation are interspersed under the influence of local variation in slope and soil; rain falls unpredictably in time and space, grass fires may destroy the available grazing within hours, water points may break down, epidemic diseases may occur suddenly (Sandford, 1983). Under these circumstances, any system of range management must be flexible, in order to adapt to the variable conditions that characterize the dry environments.

Carrying capacity. The balance between the regenerating capacity of the range and the number of grazing animals is very precarious and has often been upset.

Overgrazing is the single greatest cause of range deterioration in all parts of the world, and no satisfactory results can be expected from improvement, by various means, of the dryland areas for grazing, unless a proper balance is struck between the potential productivity of the range and the intensity of grazing (Fig. 8.4).

A major problem that must be solved in designing a range management programme is the need to estimate correctly the carrying capacity of the range. The great variation in the amount of usable forage produced from one year to another makes it impossible to determine a stocking rate that is optimal every year. Box (1981) points out that any estimate of carrying capacity determined during an exceptionally good year, will result eventually in starvation and die-off of livestock when the inevitable drought strikes.

There are two opposite approaches to assessing carrying capacity (Sandford, 1983). In the *conservative approach*, carrying capacity is considered to be the number of animals that can sustain themselves during the driest year of drought. This approach ensures that the number of animals on the range will never be excessive, but it also means that production will be at the lowest level possible, and that the potential benefits of good rainfall years will be wasted.

The livelihood of pastoralists depends mainly on the reserves in animals, forage or cash that he can accumulate in good years, and that can tide him over the bad years. Adherence to a conservative criterion for carrying capacity would mean permanent penury. Hence the need for an *opportunistic approach*, which is flexible and takes into account the degree of risk involved both in a too high carrying capacity (loss of animals, degradation of the range) and a too low estimate (loss of potential income).

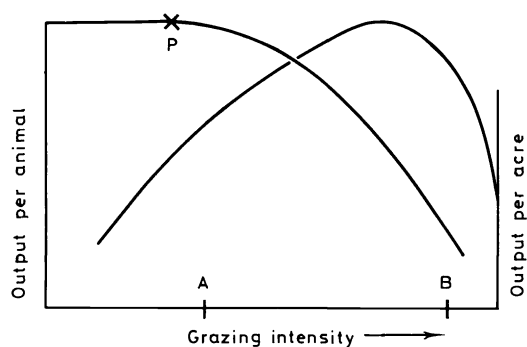


Fig. 8.4. The effect of increasing grazing pressure on output per animal and output of land. From Raymond (1968). By permission of the American Society of Agronomy, Inc., The Crop Science Society of America, Inc. and the Soil Science Society of America, Inc.

Flexibility is achieved by (a) adjusting the number of animals seasonally according to the conditions of the range; and (b) by creating reserves of forage in the good years.

Sandford (1983) considers the tendency of the traditional pastoralist to build up maximum-sized herds, as a hedge against drought; the more animals in the herd, the greater is the probability of a sufficient number surviving critical periods. Sanford thereby refutes the generally accepted view that pastoralists accumulate animals unrationally, for reasons of social prestige. He concludes that the more access the pastoralist will have to other forms of savings and investment, the less will be the need to invest in more livestock as an insurance against catastrophic losses.

In brief: a conservative strategy can have a very high cost in terms of the value of useful output from livestock foregone, through waste of unused forage, in relation to the output attainable under an efficient opportunistic strategy. "The greater the degree of variability of rainfall over time, the greater will be the opportunity cost of conservatism" (Sandford, 1983).

The problem of assessing carrying capacity is further compounded by the difficulty of obtaining relatively reliable estimates.

An assessment of the carrying capacity of the range is generally obtained by arbitrary methods and is frequently misleading. Generally, on terrain with low erosion hazards, not more than 50 to 60% of the annual growth of the more palatable perennial species may be removed (Heady, 1965). Seasonal variations are balanced by leaving part of the production ungrazed during flush growth to serve as a carry-over for the period of scarcity or supplementing by forage reserves.

Though there are differences of opinion on the precise level of grazing pressure that will give optimum productivity from the range, there is general agreement that there is a level at which overstocking causes degradation of the range. Equally, there is agreement that understocking may have undesirable effects on the productivity of the range, mainly through enabling the encroachment of undesirable species.

Minimizing effects of fluctuations in range production. For successful production of livestock on dryland range, it is essential to minimize annual fluctuations in feed supply, by utilizing high-range production during the good years to create reserves that can enable animals to survive critical periods.

It has already been pointed out that traditional pastoralists attempt to adapt to the fluctuations by accumulating excess animals when the rains have been adequate, in the hope that some will survive the dry years.

A more efficient insurance against drought is to store excess forage as fat on the animals. One version of this approach is commonly practised with sheep in Western Australia in a Mediterranean-type climate, with a fairly reliable rainfall during a short cool-weather period, followed by a long drought. Sheep are allowed to fatten during the period of lush growth, and then lose up to a third of their weight during the dry season. However, if the rains fail, the animals die, unless food reserves prepared in a more conventional way are available (Box, 1981).

Incidentally, land races of sheep in the Mediterranean region have developed their own system of reserves for hard times, namely enormous fat tails, which may be so heavy, that normal mating is often impossible without the intervention of the shepherd. The hump of zebu cattle, and of the camel, are similar reserves for critical periods.

Forage reserves; grazing systems. A number of controlled grazing systems have been devised to minimize the adverse effects of grazing during the critical growth periods of the desirable range species. The advantages claimed for controlled grazing systems are: (a) rest from grazing enables the herbage to gain in vigour and allows desirable species to produce seed; (b) livestock distribution over the range is better than otherwise, and grazing is more uniform; (c) re-seeding and brush control are possible on resting range without interference from livestock.

The disadvantages of the controlled systems are: (a) difficulty of establishing such systems; (b) the grazing animals are not allowed to choose the feed they prefer, and probably need.

Whether the advantages outweigh the disadvantages, and in particular whether they justify the additional costs involved, is a highly controversial subject. Heady (1965), who thoroughly reviewed the problem, concluded that in practice the advantages of controlled grazing were small or nil and that other management practices had a far greater impact than the system of grazing adopted.

The reasons why traditional pastoralists do not practise controlled grazing systems are generally attributed to their ignorance of the benefits to be derived from rotation, to lack of concern with range productivity because 'they can always move on elsewhere' and to the system of land tenure, whereby the land belongs to the community at large (Sandford, 1983).

In most deserts, there are usually some favoured areas with local water resources, or in which water spreading can be practised. By using this water to produce forage

reserves, to be fed only during critical periods, livestock mortality can be reduced considerably. Reserves of forage, built up in special centres in Algeria, have made it possible to reduce losses of sheep during a period of drought from 40% of the adult sheep and 80% of the lambs to 3 to 15% (Whyte, 1956). Another possibility is to offset seasons of shortage by reserves of fodder that have been built up in years of plenty from surplus forage which is either harvested and conserved as hay or is left as standing herbage on protected areas. In the Russian deserts and semi-deserts, hay is cut over 10 million hectares, mainly on the 'limans', lands in low-lying depressions.

Other possibilities are the use of fodder shrubs or trees; giving livestock access to cropland after harvest, to graze on the stubble.

Improving forage production

Improving soil moisture. The major constraint to productivity of the rangelands is the inadequate and unreliable moisture supply. Hence the importance of improving soil moisture conditions and/or attenuating moisture stress.

The three processes to achieve this objective are (a) increasing soil moisture; (b) conserving moisture; and (c) increasing water use efficiency.

Soil moisture can be increased by water spreading; (a) by directing water from ephemeral streams on to floodplains and terraces (cf. p. 136); (b) by reducing run-off and improving infiltration (cf. pp. 122–124).

The proportion of rainfall lost as run-off tends to decrease the larger the area being considered. In river basins larger than 1000 km², in arid and semi-arid regions, run-off may amount to 1% or less; whereas on small plots, it may reach 40% or more (UNESCO/UNEP/FAO, 1979).

In the southern border of the Sahel, the average annual balance under natural conditions, indicates that vegetation transpires less than 10–20% of the rainwater; about 60% evaporates, and 25% is lost as run-off. Evaporation is relatively high, because a large part of the rain falls before and after the growing period of the vegetation (Breman and De Wit, 1983).

Programmes on mechanical means for water conservation, such as contour furrowing and pitting, as well as water spreading, have been carried out in the USA, Mongolia, China, Iran, and India (Sandford, 1983).

In the USA, contour furrowing and range pitting, as well as water spreading, has been implemented on government land since 1935, on about 100 000 km², accounting for 12% of the dry rangelands of the western USA (Hadley, 1977).

Fertilizing the range. Fertilizing the range aims not only at increasing productivity but also at improving the composition of the plant cover.

Range fertilization has proven to be effective in the Northern Great Plains of the USA in areas where annual precipitation is as low as 280 mm. In warmer regions, 380 mm or more may be required before fertilization is economically feasible (Herbal, 1981). The root systems of range plants often act as sinks, thereby immobi-

lizing relatively large amounts of nutrients and enhancing the lack of apparent response of the herbage when precipitation is low (Black and Wight, 1979).

Experiments in the Sahel region in Africa have shown that even in a year with 200 mm rainfall, the application of nitrogen and phosphorus leads to an annual increase in dry-matter production, being 1.5 to 4 times higher than in the untreated area. No response to NP fertilizers was obtained where less than 100 mm fell (Breman et al., 1979/80). It should be stressed that the yield baseline, under Sahel conditions, is extremely low.

In a more recent study, in the Sahel summer-rainfall zone of 500 mm mean annual precipitation, Breman and De Wit (1983) found that productivity of the range in the southern part of the Sahel could be increased by NP fertilization by as much as a factor of five, as shown in Fig. 8.5.

Breman and De Wit come to the surprising conclusion that low availability of N and P is a more serious constraint than low rainfall. This conclusion was supported by their finding that at the end of the season, 10–20% of the moisture from rainfall was still present in the root zone. The transition from growth limited by soil moisture to that determined mainly by nutrients occurs at an annual summer rainfall of about 300 mm. The authors stress that this dividing line is not absolute and definite, but is influenced by soil fertility and the rate of run-off.

Fertilizers have shown good response in a winter-rainfall area in the northern Negev of Israel, on loess soils and with an average annual precipitation of 250 mm. In years with medium to good rainfall, primary production in NP fertilized range (150–200 kg/ha N + 50 kg/ha P) was 6–8 t/ha dry matter, an increase of 100–166% compared with unfertilized range. In a dry year, the absolute response was smaller, but the relative increase was similar (Van Keulen, 1975).

Noy-Meir and Seligman (1979) observe that annual range plants respond dramatically to N fertilization in loessial wadis in areas with as low as 75 mm annual rainfall, and show a moderate response on loessial plains at 150 mm and on stony slopes at 250 mm.

A major factor that determines the economic justification of fertilizing rangeland, is the ratio between the price received per kg of animal produce and the cost of a kg of fertilizer. The ratio, at farm level, between 1 kg of live sheep and 1 kg of N fertilizer in 1977/78 was: in the USA, 3.2/1; in India, 1/1; and in Niger (the Sahel), 2.56/1 (Sanford, 1983).

The most promising results from fertilizer application can be expected on water-spread areas and in the higher-rainfall areas. Fertilizers may also be required in conjunction with re-seeding (see below), to give introduced species a better chance of establishment and survival.

Improving the vegetative composition of the range. The composition of natural vegetation can be improved by proper management, application of fertilizers, eradication of undesirable species and re-seeding.

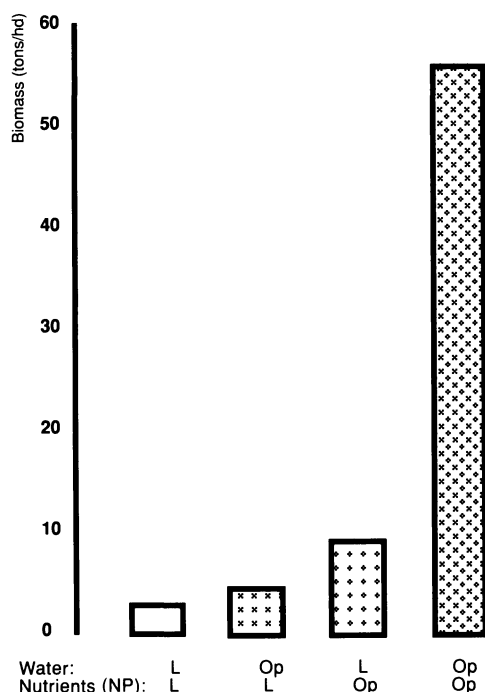


Fig. 8.5. Effect of water and nutrient supply on the yield of range forage in the Sahel. Based on data from Breman and De Wit (1983).

Desirable species in the range can be favoured by timing and length of grazing and the successive use by different species of livestock.

Brush eradication. Large areas of range become inaccessible to cattle as the result of brush encroachment. In the brush-dominated Tsavo National Park in Kenya, only 18% of the vegetative cover is consumed by grazing animals of all kinds, even in a drought year (Phillipson, 1975).

Many of the trees and shrubs, in particular in the semi-arid savannahs have little value as browse; they compete successfully with the herbaceous component for water, nutrients and light and their removal is generally likely to be beneficial. In former Rhodesia, clearing resulted in relative yield increases from about 160% to about 400% (Barnes, 1979).

Burning. Elimination of brush and other undesirable plants can be achieved by controlled burning, a method widely practised in Africa, which not only reduces brush infestation and other inedible plants, but also lessens the incidence of parasites and predators (Sandford, 1983).

The nutritional value of the forage is also improved. For example, in West Africa, burning towards the end of the dry season stimulates growth of vegetation with a crude protein content of 5–9%, compared to 2–4% in the material before burning (Sandford, 1983).

Jacobs (1977) states that the highly productive open plains of East Africa are largely the consequence of natural or man-made fires. Where administrative pressure has mistakenly been used to discourage burning, brush encroachment has resulted.

Chemical herbicides are used on a large scale in modern ranching systems, and research on their use has been undertaken in East Africa. They are, however, not being used as yet on a significant scale in Africa or Asia (Sandford, 1983).

Re-seeding. Millions of hectares of rangeland worldwide are dominated by, or being invaded by undesirable plants. Once established, woody plants cannot be controlled by grazing management and must be eliminated before improved practices, such as re-seeding, fertilizing, water spreading, etc., can be implemented (Herbal, 1985).

Numerous investigations have shown that when undesirable species, in particular scrub and bush, dominate the range and desirable species have completely, or almost completely disappeared, the only practical method of restoring the productivity of rangeland within a reasonable time, after brush eradication, is re-seeding with adapted desirable species. Simply allowing 'natural' recovery may take many years, in the arid and semi-arid summer-rainfall areas.

For vast areas, revegetation is not considered to be cost-effective because of the risks of failure involved in revegetation, and the low productivity of the rangelands. The probability of summer precipitation occurring at the right time, and in a sufficient quantity, is not very high. In southeastern Arizona, it is one in ten; and this is probably the case in many other low summer-rainfall areas. Also, knowledge about the technology needed is inadequate for many areas (Morton, 1985).

However, revegetation cannot be evaluated solely as restoring an economic resource; its major importance lies in its role of halting and reversing the deterioration of a national natural resource. Morton (1985) concludes that "Revegetation based on environmental considerations, such as soil erosion control, wildlife habitat, water quality, and stability of the watershed may justify the high monetary cost".

The problems are far less acute in the winter-rainfall areas, such as those with Mediterranean-type climates, in which re-seeding takes place during the cool season. Natural revegetation is also far more rapid than in summer-rainfall areas. The productivity of such deteriorated ranges can be restored practically and economically by sowing adapted species, provided rainfall is in excess of 200–250 mm and marginal soils are avoided.

Re-seeding the range with indigenous species and the introduction of new species of grasses, legumes, shrubs and trees, have been carried out on a significant scale in China, Iran, North Africa, India, USA, and Australia.

In Australia, considerable effort has been invested on the evaluation of introduced pasture species. Of 30 000 introductions, only 26 varieties are used widely in northern Australia. These have largely removed the specific constraint of poor feed quality during the dry season. More recent collecting expeditions have concentrated on increasing the pool of legume genotypes adapted to the arid and subhumid regions (Mott and Reid, 1985).

In the arid areas, severe management and environmental constraints have limited the use of exotic species to situations where the high inputs required for re-seeding degraded range are available and economically justified (*ibid.*).

In Western Rajasthan, India, seeding rangelands with exotic species, such as *Lasius indicus*, buffalo grass (*Cenchrus ciliaris*), Angleton grass (*Dicanthium annulatum*), and blue panic (*Panicum antidotale*) has been successful, and some species have produced fodder in excess of 3000 kg/ha (Paroda and Mann, 1979).

In the arid areas of the Sahel, India, Pakistan, Chile, Peru, and elsewhere, leguminous fodder trees, such as *Prosopis* spp. and *Acacia* spp., provide a dependable source of livestock feed and help to stabilize the range.

In sub-Saharan Africa, little re-seeding and replanting of the range has taken place. In South Africa, limited areas on private farms have been planted with cactus to serve as a forage reserve.

Improvement of livestock productivity

Livestock handling and distribution facilities. The importance of adequate livestock handling and distribution facilities for improving livestock productivity cannot be overstressed. Sufficient and strategically situated watering places, shade, fences, corrals and stock trails are essential in order to make all parts of the range equally attractive and accessible to the animals. These facilities are still lacking or inadequate in most developing countries, and should form an integral part of any range development programme.

Establishing watering points. This is closely connected with range management practices, because access to water is a key factor in controlling access to pasture.

The development of water supplies involves not only the establishment of new watering points but also changes in the use of existing supplies and the relative advantage derived by different people from the use, control and ownership of all water supplies (Sandford, 1983).

These changes can have beneficial as well as negative consequences. The beneficial effects include increased productivity of the livestock by reducing the time and energy involved in walking to water; bringing previously ungrazed land into use; making possible a change in the type of animal using the range (e.g., replacing camels by cattle or low-grade breeds by improved breeds); allowing a system of rotational grazing; making possible the growth of permanent settlements around the watering points.

Among the possible negative effects is the creation of devastating overgrazing (called 'sacrifice areas') around the water points. The radius of these sacrifice areas varies from one kilometre in normal years to eight kilometres in periods of droughts. The additional water points may increase overgrazing by increasing the number of animals and by attracting additional pastoralists to the area. As a result of the latter, intense competition may arise between different groups of pastoralists, often leading to sabotage, misuse and neglect of shared water points (FAO, 1984).

Water development is possible using different means (Sandford, 1983):

(a) *Open wells* can be dug by hand and can be undertaken by the pastoralists themselves. Overall costs are usually modest and can be met from own resources.

(b) *Dams, hafirs (tanks in India) and cisterns* depend on current rainfall or that of the previous year. Generally they supply water for limited periods. They can also be developed by own resources.

(c) *Deep boreholes* tap aquifers of fossil water or water that has accumulated in previous years and are therefore not dependent on current or recent rainfall. They can assure a year-round supply. However, they require considerable investment and their operation depends on a regular supply of fuel, spare parts and a minimum of technical know-how.

Water can be brought by pipeline from a distance (the Negev, Israel), or brought in by water tankers (Saudi Arabia, Syria). The salt content of brackish water can be reduced by small reverse osmosis or electrodialysis reversal plants (cf. p. 164).

Many of these developments have been poorly planned, implemented, or maintained. Many boreholes cease operating a short time after being drilled because of breakdowns. Dams and hafirs silt up rapidly and the water gets polluted. Competition between different user groups often leads to sabotage, misuse and neglect of shared water facilities.

To overcome these problems, a water law is required, that lays down rules and procedures on the overall level of exploitation, the groups entitled to use the facilities and under what conditions, and who is responsible for maintenance (Sandford, 1983). No less important is an effective authority for enacting the law in cooperation with the users.

Improving animal health. Disease control is a major problem facing all pastoralists. In much of dry Africa, rinderpest, foot-and-mouth disease, and bovine pleuro-pneumonia cause considerable losses, and are serious constraints in the marketing of animals from the stricken areas (Box, 1981).

Nomadic or transhumant systems facilitate the transmission of animal diseases, whilst making their control more difficult.

Improving animal health includes the following measures (Sandford, 1983): control of the major epizootic diseases and of external and internal parasites, treating wounds and injuries and routine operations such as castration and de-horning.

Improvement of livestock. If livestock improvement without adequate feeding is impossible, it is equally true that primitive breeds of livestock, with their inherently low yielding capacity, cannot make full economic use of improved rangeland, rational management and improved health – hence the need for concurrent improvement of management and of the livestock. This is generally based on upgrading locally adapted breeds, by introducing sires from improved breeds, thereby combining as far as possible the hardiness of the former with the productivity of the latter.

In many developing countries, programmes for breed improvement include the distribution of high-grade bulls to progressive farmers, on loan or sold at subsidized prices, for their own use and that of neighbours; major problems in implementing these programmes are their cost, and the danger of spreading disease (Sandford, 1983). The alternative is the organization of an artificial insemination service.

Diversification. Pastoralists tend to diversify their herds, grazing goats with cattle or sheep. Diversification improves the use of the herbage, reduces risk of total loss due to disease and provides milk at different times of the year (Sandford, 1983).

One approach to alleviate pressure on the grazing lands is stratification: the farmers in less arid areas raise grower stock, the pastoralists graze the animals until they mature and these are then fattened for market in areas where by-product feeds are available. Such a system has been applied in North-East Kenya and in Senegal. Stratification, however, requires a fairly complex infrastructure to enable the animals to move through the system, and moreover it is frequently resisted by the pastoralists.

In those areas in Ghana that are served by well-established credit unions, the habit of functioning in a money economy has been acquired by pastoralists, at least to some extent. Cattle are drawn upon as capital to be used when required. Besides biological, technical and cultural problems, there are also economic and institutional limitations. Most important is the lack of a physical infrastructure and adequate marketing facilities.

Improving livestock production by ranching

Livestock ranching is mainly found in the arid areas of North and South America, South Africa and Australia, generally on soils unsuitable for crop production (Matlock, 1981).

Box (1981) stresses that “one of the major shortcomings of ranching development in less-developed countries is the introduction of intensified schemes without the management or support facilities to properly implement and maintain them”.

All African countries have nationalized rangelands and few recognize pastoral use as establishing any claim under customary law, as is usual for cultivated land. Control then passes from communal ownership into the hands of state, company or private ranches, rich investors or new parastatal organizations (FAO, 1984). Ranching is a highly commercialized and specialized approach to improving livestock pro-

duction in regions with insufficient rainfall for crop production, imported from developed countries, with the intention of replacing traditional pastoralism.

Salient features of ranching. The salient features of ranching are:

- (a) The fencing of the area, or at least marking of boundaries making possible planned grazing procedures.
- (b) The establishment of adequate watering points, which by proper spacing make it possible to reduce localized overgrazing. Self-feeding salt installations at the right locations also induce the livestock to graze the range more uniformly.
- (c) Efficient management and utilization of the range.

The single most important factor in ensuring efficient use of the range is to balance the number of grazing animals with the amount of annual growth that can be removed without impairing the productive capacity of the range.

Ranching is usually beset by a number of difficulties. Remoteness from market and poor communications cause either high freightage costs or require the transport of the cattle 'on the hoof', with a concomitant loss of weight and quality. Because of the low purchasing power of the population of the developing countries, most of the meat has to be exported. Therefore, quality and sanitary requirements are high and the control has to be stringent. To meet these requirements, considerable capital expenditure and a high professional level are essential. Because of the fluctuations in the production of the range, the animals gain weight for part of the year and then lose much of the gain. Drought years may either oblige ranchers to sell stock at a loss or result in considerable mortality.

For these reasons, modern ranching requires a high standard of management, very large areas per farming unit and a considerable capital investment.

As a result, in most cases, ranching is in the hands of large companies or large landowners who are able to supply capital and technical knowledge when required and are also able and equipped to export the beef stock economically and efficiently from the producing areas to the consuming countries.

However, ranching does not provide an answer to the problems of the pastoralists, even as hired labour. Western (1973) estimates that the number of workers and dependents per unit of land devoted to commercial ranching in Kenya is typically less than 15% of that supported by traditional pastoralism in the same area.

Cooperative ranching has been suggested as a possible solution, with several cattle-owners combining their herds and other resources in order to make possible the provision of the essential capital development. Until recently, however, there are few examples of successful cooperative ranching in developing countries.

One such example is the strategy adopted by Syria, which has undertaken the problem of improving the living standards of the Bedouin on a broad front.

Grazing cooperatives were established to limit overgrazing. Each cooperative was given the sole right to graze a demarcated area. Each family received a license for

grazing a specific number of sheep (usually 100 to 125). Efforts were made to keep the sheep off the range at certain critical periods of the year to give the grass a chance to establish itself. A form of stratification was adopted, whereby fattening units were set up on a cooperative basis in cereal-growing areas, using locally available products.

Bedouin resistance to these measures caused difficulties; the programmes were therefore started in small areas in pilot schemes and were expanded gradually. By 1981, 105 grazing coops had been established with 2.5 million sheep grazing 6 million ha of rangeland and 55 coops with 4400 members for fattening 1.5 million sheep (FAO, 1984).

Game management – an alternative to cattle

Tribe (1970) mentions three ways in which game can be managed for the production of meat and by-products (skins, horn, bone-meal, etc.).

(a) *Game culling*, or the selective reduction of wild populations.

(b) *Game ranching*, in which wild animals are encouraged to graze in an area operated as a commercial ranching enterprise. These ranches are generally located in areas with bush savannah vegetation and not less than 600 mm rainfall. The game may graze in association with domestic cattle.

(c) *Game farming* involves the domestication or semi-domestication of the species involved. The animals (usually gazelles and buck) are grazed in fenced paddocks and may receive additional feeding. The eland has shown considerable promise: it grows rapidly; produces high milk yields; has a low water requirement; and is amenable to routine handling.

All three forms could be potentially important, though game culling and ranching appear to be the most promising (Tribe, 1970).

Advantages. The proponents of game ranching claim that the productivity of a multi-species population of wild ungulates on the range is greater than that of domestic livestock for the following reasons (Walker, 1979):

Better physiological and ecological adaptation: game animals have evolved a number of adaptive mechanisms to high temperatures and limited water supply; though they are carriers of certain diseases which are lethal to cattle, such as trypanosomiasis, foot-and-mouth, and theilerias, they themselves are not susceptible.

Greater productivity: gain in weight is more rapid, and reproductive potential is greater than for cattle. Game animals have a higher dressing-out percentage and a far lower fat content.

Problems. The state of knowledge on wildlife management and utilization is still limited and the advantages mentioned above have not been conclusively proven, hence the need to proceed with caution in advocating their large-scale economic use. Whilst the idea of game ranching is biologically sound and technologically possible,

it requires a high degree of expertise in biology and management of wild animals. Mismanagement and inadequate control may result in the destruction of an important natural resource.

The absence of suitable techniques of harvesting, processing and marketing may also be a considerable handicap to the use of game animals.

Potentials. Many enterprises in the Transvaal, Zimbabwe, and Australia have been commercial successes (Tribe, 1970). Walker (1979), however, states that in practically all cases known to him, the income from meat production on game ranches has had to be supplemented by income from safari hunting, in spite of the high animal biomass carried on the land.

The major reason for this situation is, according to Walker (1979), the marketing system. Veterinary restrictions forbid the processing and distribution of game carcasses in the same centres as domestic animal carcasses; game ranches are far from major centres and transport is costly; consequently most of the game meat is marketed as 'biltong', namely: air-dried, salted strips of meat which commands a low price.

Walker (1979) concludes that where the introduction of a comprehensive system of water supply is impossible or excessively expensive, and in tsetse-fly-infested areas, the use of adapted game species is the only viable form of ranching. Where ranching is not restricted by water or disease, it is unlikely that cattle ranching will be replaced by game ranching. The optimum form of land use in such favoured areas would probably be a mixture of cattle and game. This would however require the solution of certain veterinary problems, the choice of suitable game species, mainly on the basis of their food preferences and disease resistance, and a selection and taming programme.

High-technology schemes for desert areas

Controlled-environment schemes

The desert regions of the world are generally rich in sunlight and arable soils, but deficient in water and vegetation. Apart from irrigation, as the major solution to the development of arid lands, various high-technology schemes for desert development have been proposed, and are in various stages of planning, experimentation and pilot development.

The basic concept is to insulate crop production from the severe constraints of the natural desert environment, and provide conditions for optimum animal and plant growth, using all available resources (light, warmth, wind energy, geothermal energy, etc.).

To allow for control of the environment, the major factor in these systems, crop

production takes place in enclosed structures. This allows for control of air temperature (heating and cooling) light, water, nutrients as well as protection from adverse climatic conditions (Fontes, 1979).

The Environmental Research Laboratory of the University of Arizona has been a pioneer in this field and has established controlled environment schemes in Abu Dhabi, Carg Island, Iran, Puerto Penasco, Mexico, and Arizona, producing vegetables and high-value animal protein. These systems are presently of limited use because of high capital investments and energy requirements; research and development are needed to develop low-cost systems with reduced energy requirements (Fontes, 1979).

Controlled photosynthesis in organic wastes

The basic concept of this approach is to use animal, human and agricultural wastes as substrates for mass cultivation of algae in the desert. The warm, sunny climate of the desert is ideal for algae mass production of biomass with high protein content. The algae could also be converted into gaseous or liquid fuels, fertilizers and useful chemicals. Small communities could be set up in desert areas in the vicinity of urban centers, in which windmills and/or photovoltaics provide the energy required, urban effluents the raw material and the community the labour for biomass energy farms. The estimated cost of development would amount to 5000 US dollar/ha, corresponding to a 37 year pay-out period per community of 100 families (El-Swaify et al., 1979).

Rainfed arable cropping in semi-arid areas

Definition and problems

Dryland farming occupies the largest area of agriculture in the semi-arid regions of the world (Bowden, 1979).

For the purpose of this presentation the definitions of rainfed arable cropping in semi-arid areas is that proposed by Oram (1980): "husbandry under conditions of moderate to severe moisture stress during a substantial portion of the year, which requires special cultural techniques and adapted crops and systems for successful and stable agricultural production".

Oram (1980) lists the following climatic characteristics:

- low total rainfall, with at least one pronounced dry season;
- highly variable and unreliable precipitation during the normal rainy season;
- large year-to-year differences in total rainfall and its distribution throughout the season;

- increasing variability and unreliability with decreasing annual rainfall;
- PET exceeding precipitation at least seven months of the year;
- high-intensity rainstorms leading to high run-off and erosion.

The semi-arid regions include (a) the areas with a Mediterranean-type climate with winter rainfall; (b) tropical and subtropical savannah areas with predominantly summer rainfall; and (c) middle-latitude zones with very cold winters, hot summers and mainly summer rainfall.

The amount of rainfall that has been set, somewhat arbitrarily, as the limit of regular dryland farming, is around 250 to 300 mm annually in areas with predominantly winter rainfall and approximately 500 mm annually in areas with summer rainfall (Wallen, 1966).

It is on the fringes of the arid regions that arable cropping is most precarious, and undesirable methods of land use have led to catastrophes. These regions are characterized by the irregular pattern of annual precipitation, which varies within very wide limits.

In years of sufficient precipitation, good yields can be obtained because of the build-up of fertility during the low-rainfall years. This serves as a temptation to plough up land for cropping – especially when years of high precipitation coincide with favourable marketing conditions for the grain.

Inevitably, years of under-average rainfall follow, and crops fail more or less completely. In addition to the economic distress involved, the misuse of the land leads to severe erosion – mainly by wind.

As one moves from the drier fringe towards regions with higher annual rainfall, the prospects for satisfactory crop production improve. However, even under these circumstances, occasional years of drought and crop failures are almost inevitable.

Experience of rainfed arable cropping in various semi-arid regions of the world has shown that the ploughing-up of rangelands in high-risk regions having precipitation that is too scanty to ensure reasonable prospects of cropping should be avoided. The ‘dust bowl’ created in the 1930’s in the United States is the classic example of the dangers inherent in this type of land use.

Rainfall unreliability has led to the development of traditional farming systems in the semi-arid areas of the world, in which the emphasis is on reducing risks. For the subsistence farmer, crop failures do not simply mean a reduced income, but may result in outright starvation. Traditional methods of farming have at least proven over the centuries that they are fairly well adapted to local conditions. The fear that new and untried practices, besides requiring cash outlays that the subsistence farmer can ill afford, may fail to produce as much as the old practices, and thereby endanger the farmers’ very survival, is not irrational; on the contrary, it is a legitimate economic consideration. If we add that the average subsistence farmer is not aware that population pressure and the resultant deterioration of natural resources have in many cases made traditional production methods redundant, it is clear why risk

aversion and emphasis on stability make it difficult to introduce improved technology (Arnon, 1987).

Mediterranean-type climates

The Near East and North Africa

In the semi-arid winter-rainfall areas of the Near East and North Africa, traditional agriculture is almost exclusively based on winter cereal production: wheat in the higher-rainfall areas, and barley in the less favoured ones. These small-grain cereals have proven, through long experience, to be the food crops best adapted to the semi-arid climate. Their growth patterns coincide more or less closely with the distribution of rainfall, and they are able to survive periods of drought. The winter cereals are sown mainly after uncultivated fallow; the lower the rainfall, the longer will be the period of fallow.

The soil cultivation is superficial and does not completely eradicate weeds, so that the plant cover is apt to be rapidly restored during the fallow period. Until the beginning of this century, only the best lands were cultivated, and marginal areas were left for grazing. Yields were generally low and irregular. But in more recent years, population pressure has led to the cultivation of marginal lands, coupled with the introduction of mechanical ploughing; this has frequently led to soil erosion and crop failures.

Some annual forage crops, such as vetch (*Vicia sativa*), berseem (*Trifolium alexandrinum*), and subterranean clover (*T. subterraneum*), are well adapted to the semi-arid climate with rainfall in the mild winters. They are not used to a large extent in the traditional agriculture of these regions, but have proven their value, both for forage production and for improving the general fertility level, in the modern agriculture of Australia, for instance.

Perrin de Brichambout and Wallen (1963) state that evapotranspiration is very much the same in most parts of the semi-arid region of the Near East, and that, as a result, the limit of dryland cropping is closely related to annual rainfall. They have therefore attempted to determine the lowest amount of rainfall needed for regular dryland farming in the Near East, taking into account the variability or reliability of annual precipitation in different areas. They found that a mean annual rainfall of 240 mm, with a variability of 37%, was the normal minimum requirement for regular dryland farming in the region. Where variability was much greater, as on the slopes of Zagros in northern Iraq, a much higher annual average was required.

Allowing for crop failure due to drought in two years out of ten, it was found that the minimum amount in an individual year varied from 180 mm in areas with regular rainfall, such as Jordan, south-western Syria, and the so-called Fertile Crescent, up to 230 mm in the north of Iran – where the low winter temperatures extend the dry-farming season into the summer, with consequent high evapotranspiration. The

borderline zone for dryland farming, and hence the limit between semi-arid and arid conditions, was thus found to be between 200 and 300 mm of annual rainfall in these regions.

Crops can be grown: (a) during the rainy season, for winter crops, mainly wheat in the more favoured rainfall areas, and barley, in the drier areas. Pulses are also widely grown: lentils, peas, horse beans, chickpeas, etc. In summer (spring sowing), crops are grown on stored moisture alone, and success with summer crops is an excellent indicator of the managerial ability of the farmer. The major crops are grain sorghum, cucurbits, sesame, cowpeas, tomatoes, okra.

Loomis (1983) reports that a number of researchers in central California were consistently successful in raising 120-day summer crops of maize and grain sorghum entirely from stored moisture. Yields were high, approaching 60–70% of the level obtained in irrigated crops with moisture not limiting. Moisture was extracted from depths exceeding 3 m.

In Israel too, high yields from summer crops (mostly C4 species) grown exclusively on soil moisture, are on the same level as those obtained with winter cereals (C3 species). The amounts of rainfall are the same in both cases. These results are surprising in view of the considerable difference in evaporative demand between the two growing seasons; at Davis (central California), the optimal ET is near 3 mm/day in winter and 8 mm/day in summer (Loomis, 1983).

Intermediate crops (sown in late winter and harvested in summer) are safflower, sunflowers, chickpeas.

Semi-arid Australia

Arable cropping in Australia is practised in semi-arid regions with rainfall ranging from 250 to 500 mm (Wadham, 1961). Originally, the areas for cropping had to be cleared of trees and scrub, and then levelled. Yields were low, and very large areas had to be allocated for the individual farmstead: 259 ha was the standard for the more favoured areas, and increasingly larger amounts were allowed for the drier regions.

Progress in the early years consisted mainly of mechanical innovations and improvements – tree and stump pullers, scrub beaters, land levellers, and mechanical harvesters. Average yields actually declined, most probably because of the gradual depletion of soil nutrients that had been initially low in any case (Stephens and Donald, 1958), and exceed 680 kg/ha only once in the period from 1890 to 1905. In South Australia yields averaged only 255 kg/ha and crop failures were frequent.

The first improvement came with the breeding, by William Farrer and his colleagues, of wheat varieties that were adapted to the short Australian growing season and to mechanical harvesting. The use of fertilizers, and the introduction of the combined seed and fertilizer drill, also contributed to higher yields. The high prices and considerable demand for wheat during the years of the first World War favoured an extension of arable cropping into the arid zone. In the beginning, continuous

cropping to wheat was general; later, the system of fallowing was introduced gradually and became common by 1920.

World crop surpluses, recurrent droughts, and low prices, subsequently brought financial disaster to many of the wheat-growing farms; the payment of a government subsidy to wheat farmers became necessary to alleviate their critical economical situation. Meanwhile the continual wheat cropping, even in a crop–fallow system, caused a gradual deterioration of soil structure: soil tillage became progressively more difficult and had to be restricted to an increasingly narrower soil moisture range.

The problem of deterioration was solved by introducing a ley–wheat rotation, including specially adapted, self-seeding annual leguminous species – subterranean clovers in the more humid areas, and annual species of *Medicago* in the drier regions, which were also fertilized with superphosphate. These leguminous plants occupied the land for four consecutive years, to be followed by three years of wheat cropping. Shorter rotations, consisting of two years of clover ley followed by a single cereal crop, have also been proposed (Watson, 1963). The legumes increase soil nitrogen (originally 0.01 to 0.05% in the drier soils) to levels suitable for wheat production without additional nitrogenous fertilizers (Stephens and Donald, 1958).

Subsequently, the addition of certain trace elements to soils on which legumes had not been successful with superphosphate alone, enabled a considerable extension of the cropping areas into areas that had previously been considered sterile.

It was found that for each ton of superphosphate used on legumes, increments of 747 kg of nitrogen (Donald and Williams, 1954), 58 kg of exchangeable magnesium, and 230 kg of exchangeable calcium (Williams and Donald, 1957), were obtained. The leys served as pastures for sheep, and in due course about one-third of the total sheep population of Australia was maintained on the wheat farms.

The sheep fed on the stubble of wheat crops and on the naturally regenerating or sown pastures – a system of rotational land use that proved to be very well adapted to the semi-arid agriculture in Australia. It benefits crop and animal, economizes on fertilizer use, and helps to control weeds as well as to reduce erosion on cultivated fields.

Semi-arid tropics and subtropics

Shifting cultivation

Definition. Shifting cultivation has been defined as “a continuing agricultural system in which the cropping period is shorter than the fallow period” (Sanchez, 1973). It is a farming system whereby the production of annual crops and semi-perennial crops is alternated with periods of vegetative fallow. The two main types are bush–fallow in the forested areas, and grass–fallow in the savannah areas.

At the end of the fallow period, the vegetative cover is slashed, dried and burned (in Latin America the system is called ‘roza y quema’ – slash and burn). The soil is not

cultivated before planting, but with the onset of the rainy season, the crops are planted in a layer of porous soil that is rich in organic matter. The cleared land is usually free from weeds and the soil has a reserve of plant nutrients in addition to those contained in the ash of the burned plant material – hence yields are at first quite fair.

Because of the removal of the protection of vegetative cover, and the consequent exposure of the soil to sun and rain, a rapid loss of the accumulated organic matter occurs. The considerable leaching of plant nutrients and their additional removal by the harvested crop, also cause a rapid decline in soil fertility. Yields therefore decline steeply as fertility is exhausted and the clearing is invaded by grasses and other weeds.

Shifting cultivation is far less effective in maintaining soil fertility in the savannah zones than in the tropical forest zones. The grass and brush vegetation of the former is only capable of storing relatively minor amounts of nutrients during the fallow period, so that the contribution of litter and ash deposited in the soil is very small. Regrowth is retarded by annual burning, which is generally resorted to in order to provide a flush growth of grass for the grazing cattle. Though leaching, due to rainfall, is less serious than in the humid tropics, the rule is “a vicious circle of poor fallows leading to poor crops” (Nye and Greenland, 1960).

Duration. Abandonment occurs when the farmer estimates that he will have to expend more labour on weeding than on clearing a new site. An additional consideration is that clearing can be effected in the dry season, when there is little else to do, whilst weeding must be carried out during the growing season. Natural growth is allowed to take over, which rapidly suppresses the growth of weeds that could no longer be controlled during cultivation.

So long as abundant land is available, shifting cultivation yields better returns in terms of kilograms of grain per man-hour of labour input, than does settled agriculture when using equally primitive methods of production (Clark and Haswell, 1971). Shifting cultivators in Tanzania were able to produce 100 kg of rice with 16 man-days of labour, whilst semi-permanent farmers in the same area required 21 days (Collinson, 1972).

Taking into account the prevailing levels of crop production, shifting cultivation is an entirely rational system that can be maintained indefinitely – as long as the biological equilibrium is not upset through overshortening of the fallow period. Labour requirements are relatively low: the heavy work involved in clearing is mainly done by fire, while soil fertility is regenerated by nature, and weeds are suppressed by the natural vegetation during the fallow period.

Transition to permanent cultivation. The system of shifting cultivation is successful as long as: (a) the cultivation period is not too long, resulting in a level of fertility too low to enable a relatively rapid regeneration of the natural vegetation; and (b) the fallow (or resting) period is sufficiently long to redress the impairment of soil produc-

tivity that occurred during cultivation and the build-up of weeds. All this, of course, holds provided practices are followed that do not provoke significant soil erosion (Greenland, 1974).

When these conditions can no longer be maintained because of increasing population pressure, the system breaks down and a permanent type of farming system becomes an unavoidable step forward (Fig. 8.6).

The changes that occur in the transition from shifting to permanent cultivation in Senegal have been described by Charreau (1974).

Fields become permanent, stumps are completely removed and cultivation by oxen is introduced. At first, ploughing is only resorted to every four to five years, to incorporate grass-fallow, green manures or crop residues. Otherwise, crop residues are burnt and only superficial cultivation is practised. In the year prior to fallowing, millet or sorghum is sown, cut for forage and the ratoon crop, after first being grazed, is ploughed under. The recommended cropping sequence in Senegal, during this stage, is: fallow or green manure (one to two years); groundnuts; pearl millet or sorghum; groundnuts or cowpeas.

With further population pressure, cropping becomes continuous, without resting periods of fallow or green manures. The incorporation of crop residues, including straw of short-season cereals, is frequently resorted to and has been shown to have the same beneficial effects as the green manures.

Subtropical Africa

The Sudanese Sahel consists from the agricultural viewpoint, of two distinct regions (Cochemé and Franquin, 1967):

(a) *A northern region*, bordering on the Sahara. Like the semi-arid region to the north of the Sahara, this region is one of cereal monoculture, with an alternating

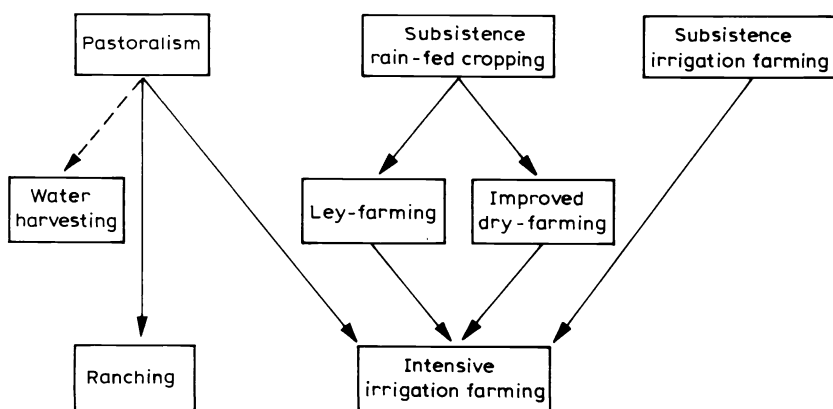


Fig. 8.6. General pathways of change from traditional land use in the dry subtropical regions.

cereal-fallow sequence. However, wheat and barley are replaced by pencillaria, which is the only grain crop that is successfully grown. Sorghum is also grown on inundated lands, after the waters recede.

The northern boundary of this region is difficult to define precisely, as it moves in the direction of the Sahara or southwards according to the prevailing cycles of wetter- or drier-than-average years, respectively. For a long period of years, the northern limit approximates the isohyet of 250–300 mm.

(b) *The southern region*, of 'extensive polyculture', in which millet, sorghum, niebé, groundnuts, cotton, and maize, can be grown, under a rotation scheme in which an annual crop alternates with fallow.

This region comprises a number of subregions, in order of increasing precipitation:

Subregion A: principal crops: pencillaria (or sorghum) and niebé.

Subregion B: principal crops: pencillaria (or sorghum) and groundnuts; secondary crop: niebé.

Subregion C: principal crops: groundnuts, cotton; secondary crops: pencillaria, niebé, maize.

Subregion D: principal crops: maize (or sorghum or pencillaria), groundnuts, cotton; secondary crops: tuber crops (manioc), rice, fonio.

The majority of the population of the Sahel depends on crop production for their livelihood, and agriculture is therefore the key to survival for the region (Bowden, 1979). Crop yields are low: on average, grain yields of rainfed crops are generally in the range of 250–500 kg/ha. Crop failures are frequent, due to the erratic rainfall and the extremely high potential evaporation. Grazing animals supplement the food supply, and for part of the population, pastoralism is the only source of income (Bowden, 1979).

The Indian subcontinent

Crops. Traditional agricultural production is based on a restricted choice of crops adapted to low fertility and moisture régimes. In Central India the main crops grown are sorghum, chickpea and to a lesser extent safflower; grown either alone or in intercropping combinations.

In the North Central Plains, the main crop is wheat, mostly grown as a sole crop, but occasionally intercropped with chickpeas (Willey et al., 1989).

Other crops grown in the semi-arid areas are: millets, *Cyamopsis tetragonoloba*, *Pennisetum*, mung bean, sesame, and *Vigna radiata*.

In the hot semi-arid regions the major crops are cotton, groundnut, maize, pearl millet (bajra), sorghum (jowar), wheat, rice, millet, pulses, and oil seeds.

The cropping patterns are still mainly traditional and subsistence-oriented. Low cropping intensity and inefficient inputs result in low yields.

Population pressure has resulted in an extension of cultivation to marginal and submarginal areas, leading to soil erosion, and still lower productivity. The tradi-

tional technology for crop production is now barely able to meet the needs of a constantly increasing population.

Fallowing. In semi-arid India, most of the dryland is left fallow during the rainy season. In the areas of low and erratic rainfall, bare fallowing during the rainy season, and thereby allowing the rainfall to accumulate in the soil, is a justifiable traditional practice that allows the farmer to grow a relatively assured crop on stored moisture (Willey et al., 1989). Sowing is done at the end of the rains or shortly afterward. Usually, a single crop is grown annually.

Willey et al. (1989) point out that while the traditional system of rainy-season fallow is fundamentally sound where there is only sufficient moisture for a single crop, it leaves little room for improving the system per se. Productivity increases can be brought about by improvements in the individual crops, and by intercropping.

In the more humid parts of the Indian subcontinent (where average annual precipitation exceeds 750 mm), the Vertisols are the predominant soil type.

Here too, in traditional management, the land is usually fallowed during the rainy season and cropped only in the post rainy season on stored soil moisture, though the more abundant rains make possible a longer period of cropping, and much less risk of crop failure is involved. The main justification for fallowing during the rainy season is that the wet soil becomes too sticky and difficult to manage and the crops may suffer from waterlogging.

Yields are generally low: sorghum: 500–900 kg/ha; wheat: 300–700 kg/ha; chick-pea: 200–500 kg/ha; safflower: 300–500 kg/ha (Virmani, 1987).

Fallowing during the rainy season is responsible for high soil and water losses. Of the total annual rainfall, up to 70% is lost, of which about 2/3 is lost as evaporation and deep percolation and the rest as run-off (Virmani, 1987).

Growing only post-rainy-season crops in these wetter areas is therefore a very inefficient use of the abundant rainfall (Willey et al., 1989).

The International Crops Research Institute for the Semi-arid Tropics (ICRISAT) has invested considerable research on solving these problems, and has developed a new technology for this purpose (cf. p. 375).

Contingency systems. The most difficult situations in the semi-arid areas are the less assured areas where average rainfall is just below sufficient for a single annual crop. In years of good rainfall, good crops can be produced in either the rainy season or the post rainy season. For these areas, some kind of contingency system is needed, so that the farmer can cash in on the good years, but still be safe in the poor years (Willey et al., 1989).

These authors note that traditional farmers already use some contingency methods. If the rains are good, and arrive early, farmers may sow very early maturing, rainy-season crops, such as mung bean or pearl millet. If drought stress becomes

severe at a later stage, it is possible to thin the crop, using the thinned material as fodder.

Increasing productivity. The basic needs of agriculture in the semi-arid areas, according to Dakshini (1985) are to preserve the ecological balance and increase productivity. He suggests that this can be achieved by diversification, utilizing intercropping with guar, castor, *Cenchrus ciliaris* and recycling run-off water.

Far-reaching changes in rain-fed cropping have taken place since the 1960's following the introduction of the high-yielding varieties of wheat developed by CIM-MYT (cf. p. 308). These, combined with a package of improved practices, and a major extension campaign, have led to significant increases in yields.

Middle-latitude dry regions

Semi-arid regions of Eurasia

Unlike the middle-latitude areas in North America, where large areas of similar climate, vegetation, and soil are found, the Eurasian steppe (semi-arid regions of the Russian Plain, Caucasus, and Central Asia) has an extremely variable physical environment. Areas of black and chestnut soils with high natural fertility are found in the Ukraine and elsewhere (Kovda, 1961), but much of the area is sand, loess, alluvium, salt pans, marshes, and rocky terrain. Surface or groundwater may be abundant in one place and non-existent a short distance away (Bowden, 1979).

The earliest attempts at farming, during the Neolithic period, were of necessity on a very small scale: the thick, tough steppe sod could not be penetrated by the simple and primitive implements available at the time. It was only after the invention of bronze and iron tools, in the middle of the first millennium B.C., and the start of the use of draught animals, that the virgin black soil could be cultivated on a relatively extensive scale.

Burning the plant cover and sod was an essential part of the primitive farming system practised. Hard spring wheat and millet were the principal crops, though barley, hemp, and flax, were also grown. By the 8th–9th centuries A.D., the three-field rotation system (winter crops, spring crops, fallow) predominated in Kiev-Rus, the large feudal state. A wide variety of crops were grown, including winter and spring wheats, rye and millet, barley, peas, hemp, flax, poppies, buckwheat and lentils. The limit of dryland farming was roughly the isohyet for 350 mm annual rainfall (Kovda, 1961).

The Mongolian invasion by Genghis Khan in the 13th century destroyed the agricultural economy of Kiev-Rus. The cultivated land was largely abandoned, and arable farming was replaced by the nomadic stock raising of the invaders. Farming in the area was resumed after the expulsion of the Mongols, and again became based on the previous system of the three-course rotation. In the 18th and 19th centuries, arable cropping gradually spread from the black-earth steppes of the Ukraine and

central Russia to progressively drier regions in the Crimea, Caucasus, and the Volga area, in which large areas of black earth as well as chestnut soils were brought under cultivation down to the 250 mm isohyet. In addition to the three-course system in the more humid parts of the region, long-term fallow was practised in the drier parts. Here, droughts were relatively frequent, 23 being recorded during the 19th and first half of the 20th centuries.

Improved techniques initiated in recent years consist of mechanized operations aimed at completing all farming activities during the seasonally optimal periods – apart from deep autumn ploughing, snow retention on the fields, and the use of fallow.

In the semi-arid Soviet central Asian region, most of the annual precipitation (200–250 mm) occurs during the cool season; summer precipitation is either sparse or entirely absent. Spring rains here bring the soil to field capacity to a depth of 100–150 cm, and make possible a form of dry-farming called ‘bogara’. The main crop is winter wheat. Below a depth of 200–300 cm, however, soil moisture is always at the wilting point or below. By autumn, a wheat crop will have exhausted most or all the available moisture, but approximately 70 mm of water will generally remain available for the following wheat crop; this water, together with later precipitation, makes it possible to obtain a reasonable yield. The summer soil moisture deficit coincides with the maturation of the cereal.

A major constraint to agriculture is the prevalence of hot dry winds throughout the summer – the *sukhovey* – which can ruin a rainfed crop in hours and severely damage irrigated crops (Kovda, 1961).

In the summer-dominant rainfall area, crop production is mainly between the 500 and 700 mm isohyets. Potential evaporation exceeds rainfall in all months. A single crop is grown each year: wheat (in winter), or sorghum (in summer), are the main crops.

Because of the low and variable rainfall, there are two soil water management options: (a) *fallow*: the traditional method to store water in the soil prior to planting, and (b) *opportunity farming* now being increasingly adopted by farmers. This consists in sowing only after what is considered a sufficient rainfall for crop establishment: 30–50 mm, depending on the amount of water stored in the soil (Coughlan et al., 1989).

The Great Plains of the USA

The Great Plains are a region of predominantly summer rainfall and constitute the principal wheat-producing area of the USA. Here, ‘dry-farming’ as a scientific method for producing crops under limited moisture, was developed.

Historical background. The Great Plains were formerly known as ‘the Great American Desert’, and were shown as such in school atlases until the 1850’s. It was gener-

ally assumed that the region was similar to the Sahara Desert. This misconception delayed the beginning of farming in the region, and it was only in the 1860's that its potentials for cereal production were recognized (Hargreaves, 1957).

The expansion of the railroads, a reduction in Indian raiding, land policy favourable to settlement led to a rapid increase in dryland farming (Cannell and Dregne, 1983).

In Texas, the land was managed primarily in large units for cattle ranching. Crop production was at first slow to develop, and occurred mainly on the best soils. In Oklahoma, in order to obtain cash for their survival, farmers sold half their holdings of the 65 ha allocated to each homestead. It then became necessary to plough most of the land on the farm, regardless of slope or soil depth. "Without modern conservation methods, erosion took its toll, soils became less productive, and the plight of the farmers continually increased, culminating in the severe drought and depression of the 1930's" (Johnson et al., 1983).

Dry-farming. The beginnings of dry-farming were greatly influenced by mistaken theories – in particular that maintaining a 'dust mulch' on the soil surface by frequent cultivations would break up the soil capillaries and thereby prevent loss of water by evaporation. European-type tillage equipment was used that pulverized the soil.

It was further assumed that very deep ploughing and subsoiling would increase water uptake by the soil, and that plants would obtain their water by capillary movement from a water table. Dry-farming practices were accordingly used on a large scale that was made possible by advances in agricultural machinery. By 1930, practically all the land of the Great Plains had been ploughed and the native short-grass cover was almost extinct. The maintenance of a fully pulverized soil surface increased wind erosion and reduced moisture infiltration into the soil. From 1931 onwards, a succession of droughts struck the region; the results were not only financially catastrophic but caused widespread soil destruction as a result of wind erosion.

The economic repercussions of an alternation of periods of favourable years with a series of drought years are vividly illustrated by the following, earlier example: in eastern Montana during a period of twelve years (1905–16), rainfall was 26% above average. In 1916, dryland farming reached its maximum extension. Then started a period of below-average precipitation, which was to continue for 23 years. After four successive years of drought in eastern Montana, during the period 1917–20, 38% of the State banks and 30% of the National banks in Montana went bankrupt; 20% of the farms were abandoned, 50% of the manufacturing concerns ceased work, 50% of the retail businesses closed, and 15% of the population migrated elsewhere (Lomasson, 1947). Yet this was in a period of high wheat prices and demands elsewhere.

The magnitude of this catastrophe has since served as the classical example of the danger of adapting land use to the conditions pertaining during favourable periods, instead of developing a stable agricultural economy that is adapted to the entire range of possible climatic conditions.

Modern farming systems. Following the disastrous effects of 'dry-farming', the key to successful dryland farming was found to be the use of systems and practices that can take advantage of the favourable years (Stewart, 1989), whilst major attention was given to minimizing soil and water loss hazards.

New tillage methods and equipment reducing soil erosion were adopted, such as contour listing, contour cultivation, terracing, stubble-mulch farming and minimum tillage.

Wheat was, and still is the major crop throughout the region, and fallow plays an integral role in the overall wheat production system. In the southern areas winter wheat dominates (fall sown, winter vernalized, followed by growth and maturation in spring); in the north, spring sowing is the rule (Loomis, 1983). The value of fallow ranges from minimal in some areas to absolutely necessary in others (Greb et al., 1974).

In describing the evolution of land use of the Great Plains Region. Cannell and Dregne (1983) write: "Research, along with the practical experience of perceptive farmers, has turned the 'Great American Desert' into the breadbasket of the world. Risk of crop failures during the inevitable fluctuations in annual and seasonal precipitation and in the length of the growing season has been lessened. Improved management techniques, better adapted cultivars, crop insurance and disaster assistance programs, more suitable tillage practices, advances in soil and water conservation methods, and other changes have increased stability in dryland agriculture, especially during the last 40 years".

Bowden (1979) in his description of contemporary farming in the North American semi-arid plains, writes: "the entire management system is at the top of the technology ladder. Giant tractors, equipped with air conditioners and taped music to comfort the operator, pull one-way ploughs and other machinery of 40 m swath over hundreds of hectares per day. Conveyors, harvesters, pickers, hoists, cleaners, grain dryers, and a myriad of other mechanical devices create an environment where a seed of grain may be treated, planted, and harvested, or an animal raised and sold without ever being touched by a human hand or handled with any direct human power".

As a result of the most advanced technology, the region produces approximately 12% of US-Canadian food, though it has only 0.5% of the population of the two countries. Despite the impressive technology, Bowden notes that "the North American steppe has economic and environmental problems. The massive ploughing and overgrazing of the prairie grass has virtually destroyed this grassland ecosystem. Soil erosion and fertility depletion continue despite all the mechanical gadgetry and scientific analysis and the various government agencies assisting the farmer".

Potentials for improvement of rainfed agriculture

In rainfed crops, improving certain simple cultural practices, that do not require expensive, purchased inputs, such as more careful tillage, better stands of plants,

timely sowing and weeding, moisture conservation, can all contribute to improved yields.

By themselves, however, improved husbandry practices have limited effects on yield, and cannot bring about a marked expansion of production. Even an improved crop rotation without fertilizers will be largely ineffective. However, in the early stages of development, improvements in husbandry are extremely important, as they build up traditional agriculture to a point where a qualitative change becomes possible. They increase the farmer's ability to buy more costly inputs, such as fertilizers and insecticides, and enhance the effects of the latter. In order to achieve a breakthrough in yields, a 'package' of improved practices becomes essential.

Crop rotation, appropriate tillage methods, the use of improved and adapted varieties, in conjunction with fertilizer application and crop protection, have proved able to effect dramatic increases in yields, even in the areas with problematic moisture régimes.

Marginal rainfall areas

Mediterranean-type regions. Fallow. In the transition areas between aridity and semi-aridity, with just sufficient rainfall to make cropping possible provided suitable measures are taken, alternating cereal and fallow so as to conserve moisture from one year to the next and thereby producing a crop on the combined precipitation of two seasons is the procedure most generally adopted as a first step towards modernization. Although a high proportion of the rainfall stored in the soil during the fallow period is generally lost, the additional 80 to 100 mm or so may make the difference between success and complete failure of the succeeding crop in regions with marginal precipitation.

In Australia, in the wheat-growing regions with an annual precipitation of 250 to 375 mm, experience shows that the fallow-wheat sequence usually assures the farmer of a crop, whereas continuous wheat would generally be a complete failure. More important still, the additional moisture is generally a prerequisite for obtaining economic returns from the package of improved practices mentioned above (Wadham, 1961).

Integrated crop/livestock systems. An alternative solution, which has proved to be very effective, is based on an integrated crop-animal husbandry farming system. The key to this system consists of a ley rotation adapted to marginal rainfall conditions, and based on alternating periods of two, or more, years of annual, self-seeding legumes – grazed by cattle or sheep – with one or more years of grain crops. This system has a built-in autoregulatory device ensuring a constant, albeit fluctuating, income. In the good rainfall seasons, the legumes and the stubble of the cereal crop produce year-round grazing (provided the number of head of stock is properly adjusted to the carrying capacity), whilst good grain yields are harvested. In the poor rainfall seasons, the relatively low production of the legumes is supplemented by grazing the cereal fields which have no prospect of producing a satisfactory grain crop. What

would have been a total loss in an exclusively grain-producing system will give a fair yield of forage, even in conditions under which no grain is formed (Watson, 1963).

This integrated system of animal husbandry and cereal cropping, widely used in the dry regions of Australia, also has the advantage that inputs are relatively low: the annual legumes are self-seeding, so that no tillage or only a minimum of tillage is required. Only phosphatic fertilizers are needed, and if they are applied in excess of the current crop requirements, the residues are not wasted. The legumes provide all the nitrogen that is required by the cereal crop; in a very good year, however, additional nitrogen may be top-dressed. The cereal can be seeded into the legume stand by means of a chisel drill without additional tillage; excessive legume volunteer plants in the cereal can be controlled by herbicides. Grain volunteer plants in the legumes provide balanced grazing. Perennial weeds such as Johnson grass (*Sorghum halepense*) and Couchgrass (*Cynodon halepense*) are kept in check both by the grazing and by the competition of the cereal crop.

Water storage (cf. p. 122). The collection of surface run-off during periods of heavy rainfall and its subsequent use during dry periods, markedly reduces the risks of rainfed agriculture. For example, in operational-scale research watersheds, yields of maize and sorghum were doubled by a supplementary irrigation of only 50 mm, given after a 30-day dry spell that coincided with the grain-formation stage. If the rainy season crop does not require, in a good year, any supplementary irrigation, the stored water can be used for a dry-season crop.

Adequate rainfall areas

In areas with adequate annual average rainfall, the dominant causes of low and variable crop yields are:

(a) The frequent occurrence of periods of soil moisture stress. Erratic rainfall during the rainy season (often too little water and sometimes too much) and considerable variability between seasons are the major characteristics of these areas (Kampen and Burford, 1980).

(b) Low soil fertility, due to exhaustive practices of crop production. The deficiencies are mainly, as a rule, nitrogen and phosphorus.

The two factors – soil moisture régime and soil fertility – are closely related. The uncertainty of response to fertilizers due to the erratic rainfall makes fertilizer application risky; the resultant low soil fertility is conducive to low water-use efficiency in years of above-average rainfall. The basic problem is therefore to devise a type of crop rotation that will raise the level of soil fertility, thus making it possible for each crop to benefit fully from the favourable moisture régime prevailing during its growing period, as well as from any application of modern inputs.

Mediterranean-climate regions. Leguminous crops that are not allowed to mature seed, but are used for pasture, soiling, hay, silage or for turning under as green

manure, have been shown to be highly effective for improving soil fertility. They also enhance the response of the cereals to other factors affecting production (cf. Ch. 16).

Integrated crop/livestock systems. Including forage crops in the crop rotation implies the integration of animal husbandry with arable cropping. Small farms in which this form of husbandry is practised often use animal power to produce crops for domestic use, for feed and for sale; they also have livestock products for their own use and for sale. The livestock, besides draught animals, usually consist of small stock: pigs, goats, sheep, poultry and rabbits.

The farmers practising integrated husbandry are less dependent on the vagaries of market prices, labour is used more fully and throughout the year, and the farmer's family is better fed.

Occasionally, the arable cropping and animal husbandry are not combined in single farm units, but in separate units within the village or locality, each specializing in one or the other direction. Dairy farming is an example, whereby reciprocal sales of forage, grain, vegetables, on one hand, and dairy products, on the other, form a fairly self-contained system, leading to more self-sufficiency in food needs, feed, fuel and manure, on a local scale (FAO, 1984).

Integrated crop production and animal husbandry is applicable both to traditional farming systems and to commercial farming.

Semi-arid tropics and subtropics. A considerable amount of research work on improving crop production in the semi-arid tropics and subtropics with summer rainfall has been carried out in recent years at the International Crops Research Institute (ICRISAT). This work has advanced to the stage at which practical proposals have been pilot tested and applied on the farm, enabling practical application of a new technology devised for summer-rainfall tropical and subtropical areas, with adequate precipitation.

The three basic components of the new technology are: improved genotype, improved management of land and crops, and use of fertilizer (Virmani, 1987).

Land is developed into watersheds of up to 25 ha, to enable farmers within the watershed to improve their management of soil, water and crops.

A *broadbed-and-furrow system* (BBF) is established across the natural slope, with a constant grade of 0.4 to 0.6%. The system consists of graded 100 cm wide beds separated by 50 cm wide furrows; with moderate rainfall, water is retained in the furrows; when heavy rainfall occurs, excess water drains into grassed waterways; drainage and workability of the heavy soils are improved. The wide beds allow for considerable flexibility of row arrangement for both sole and intercropping systems (Willey et al., 1989).

The run-off water is either drained out of the watershed, or stored in tanks for later use as supplemental irrigation (Fig. 4.12).

Primary tillage. Primary tillage to loosen the soil and prepare a rough, cloddy soil surface, is carried out just after harvest of post-rainy crops (February–March).

Draught power requirements, using an improved tool carrier, are about 30% lower than in the traditional system. The clods gradually disintegrate, and finally shatter by blade harrowing soon after the first pre-monsoon rain, thereby providing a satisfactory seedbed.

Sowing. The crops are planted in the dry soil, just ahead of the monsoon rains, to avoid sowing in wet, sticky soil and to ensure early establishment.

Intercropping. Traditionally in India, a single crop of sorghum, millet, or castorbean is grown during the rainy season on Alfisols and shallow to medium Vertisols. On deep Vertisols, soil and management problems, and crop production risks during the rainy season, have led to cropping only during the dry season (cf. p. 368). Research at ICRISAT has shown that by establishing a crop during the early rains on these problematic soils, these problems can be avoided, water is more efficiently used and a possibility is created for double-cropping by means of intercropping a short-season with a long-season crop, or sequential cropping with two short-season crops (Krantz, 1981).

Pigeonpea, as the long-season crop, can be intercropped with maize, sorghum, soybean, cowpea, sesame, or sunflower. In the sequential system, maize, sorghum, or soybeans can be followed by wheat, chickpea, safflower, or post rainy sorghum.

The new technology has enabled considerable improvement in erosion control, moisture conservation, and higher rainfall use efficiency. Yields were increased four-fold, and variability in yields was much lower.

Evaluation. The technology described has been evaluated in numerous farm tests in a few agroclimates of the Indian semi-arid tropics with moderate but dependable rainfall. Under farming conditions, gross profits from the improved technology were two to five times higher than those from the traditional system, involving a single post rainy season crop. The additional expenses required gave a marginal rate of return averaging 230%. Employment increased by 300–400 person hours per ha, employing about twice as much labour as the traditional methods (Von Oppen et al., 1989).

Willey et al. (1989) observe that the BBF system, producing two crops, each of about 100 days to maturity, can be difficult to manage, and incurs considerable risk. Harvest of a 100-day rainy season crop occurs roughly at the cessation of the rains, and a good establishment of a post rainy season crop depends on end-of-season showers. Another problem in farming practice is the difficulty of achieving a rapid turn-around between crops. Harvesting, threshing, storing or marketing the crop may leave the farmer too little time for establishing a second crop. In the on-farm tests mentioned above, the farmers involved found the proposed system very demanding and risk prone.

Irrigation agriculture

Early subsistence irrigation

Sedentary agriculture was established early in large, contiguous areas along great rivers, such as the Nile, the Tigris, the Euphrates and the Indus; in isolated pockets of well-watered oases of the deserts; more precariously on the floodplains of the streambeds in the deserts; and on the semi-arid fringes of the desert in which rainfed crops were produced.

In Mexico and Peru, the indigenous cultures were based on the need to organize irrigation systems, which made possible the development of sedentary agriculture.

Irrigation farming has considerable cultural implications. It made possible the growing of food for large populations, not all of whom had to be occupied in agriculture. This gave impetus to technical inventions, such as loom weaving and the wheel, and to cultural achievements such as writing, the development of mathematics, and artistic advances.

With the expansion of the irrigation networks, a well-developed social organization became a prerequisite for the proper maintenance of irrigation dams, channels, and structures; also needed were the enactment of laws safeguarding water rights, and the supervision of their proper distribution. A central authority, usually based on a theocracy, became established over a large areas which gradually evolved into an irrigation state. This occurred in Mesopotamia and Egypt (4000–3000 B.C.), and in China (around 2000 B.C.).

When the irrigated areas had reached their full expansion and were no longer able to feed the growing population of the State, the stage was set for expansion by conquest of neighbouring territories and transformation of the State into an empire exacting tribute from the conquered peoples. Central authority passed from the theocracy to a military establishment.

Empires which developed out of the irrigation states began with the Sumerian Dynasty in Mesopotamia, the Early Dynasty in Egypt, and the Chou periods in China.

These empires subsequently disintegrated; their decline can be attributed to conquest by stronger forces, to revolts of the dominated peoples, to a weakening of central authority and the consequent neglect of the complex infrastructure needed for maintaining irrigation farming, or alternatively to the loss of soil fertility due to salinization and waterlogging of the soil.

In most cases there was probably an interplay of two or more of these different factors, of which loss of soil fertility on large tracts may well have been the initial one.

After a relatively long period of decline in production and in population, the whole cycle might begin again a number of times, as was the case in Mesopotamia, Egypt, and China.

Floodwater farming

A very crude form of irrigation, called floodwater farming, has been practised since earliest times in the dry regions of the Old and New Worlds.

A typical example of Old World floodwater farming is the African floodplains found in many African river basins. They accommodate seasonal floods, and then shrink in size and depth when the floodwaters retire. These floodplains cover about 30 million ha. The best known is the Sudd, on the White Nile; with 9 million ha, it is the largest swamp in the world.

These floodplains help to control floods and stabilize water flow, trap sediment, and are highly productive for fish, meat and grain production (Barghouti and Le Moigne, 1990).

Special farming systems have developed in the floodplains, supporting large populations, producing fish, meat, rice and other grains. The floodplains have regional hydrological impacts, such as flood control, flow stabilization, and sediment trapping. They also have considerable ecological importance because of their large populations of wildlife.

On the debit side are the huge amounts of water that are lost by evaporation from the floodplains (estimated at 70% of the incoming flow in the case of the Sudd and 50% in the Niger Inner Delta), which could be used for irrigation or other purposes. The Jonglei Canal bypasses the Sudd for the express purpose of reducing the water losses by evaporation; the south Chad project in Northeast Nigeria derives its water from the floodplain.

No estimate has yet been made of the economic, social and environmental costs resulting from the ensuing reduced swamp areas (Olivares, 1990).

Floodwater cultivation in the New World

A very simple and primitive form of floodwater cultivation was practised in what is now the south-western USA, by a number of Indian tribes along the Gila and Colorado Rivers (Gulhati and Smith, 1967). Floodwater farming was also practised by the Hopi Indians and other tribes for whom it is still the dominant form of cultivation (Armillas, 1956).

The preferred sites for floodwater farming are the arroyo (wadi) mouths, where the silt deposited by the floods has built up a shallow fan. The ratio of cultivated field area to the arroyo watershed varies from 3 to 6 : 100. The water is distributed over the fields by the building of low earthen dams. During floods, water backs up behind the dam and saturates the soil. After the floods subside, the Indians plant maize, squash, and other crops.

Other sites are located on the floodplains of the main valleys and/or low floodterraces of large arroyos. The floods are sometimes diverted by the construction of simple earthen dams, about 30 cm high, which last for only a single season; a more permanent type of check dam is built of brush and loosely piled stones.

Where seasonal floods were very variable, with years of no floods interspersed with years of floods of destructive force, the agricultural economy was extremely unstable and subsistence had to depend to a large extent on food gathering and fishing. Where floods were more dependable, and occurred in both summer and winter, two crops a year could be grown and agriculture was the main source of subsistence.

Summing up, it may be said that, under certain conditions, floodwater farming was the only, and essential method for producing crops in the desert. The intensity and number of floods determine the size of the area that can be sown. The large fluctuations from year to year make such farming a very precarious source of livelihood; in certain years, the floods may be rare or short-lived, and the soil will not be moistened to a depth that is sufficient to justify sowing.

It therefore appears doubtful whether a viable modern agricultural economy can be based on this form of crop production, especially as cultivation is possible only in relatively small and scattered strips and patches, making mechanization uneconomic. The method may, however, have its uses for creating local reserves of forage. Modern methods of using run-off water are also being developed, and are discussed in Ch. 4

Irrigation agriculture in the Old World

Four great valley civilizations flourished in early times in the Old World: those of the Nile, the Tigris–Euphrates, the Indus, and the Hwang-Ho. All four regions are characterized by extremely light precipitation and high summer temperatures, and were therefore dependent on irrigated agriculture.

Very little is known of the early history of the civilizations of the valleys of the Indus and the Hwang-Ho (Drower, 1955); by contrast, considerable information is available on those of Egypt and Mesopotamia – to which regions we will accordingly confine ourselves.

Evolution of irrigation agriculture in Egypt

The rainfall equivalent of the annual irrigation supply of Egyptian agriculture works out at approximately 2000 mm. Yet with only a narrow coastal strip receiving an average of as little as 125 mm of rainfall, Egypt belongs to a typical arid zone (Hamdan, 1961).

Prehistoric. According to Butzer (1958), the Nile Valley was occupied by Man as a hunter or food gatherer for at least 10 000 years before agriculture was attempted. During the period before the Nile was contained by embankments, only the areas

lying above the high-water mark could be inhabited. It is conjectured that the inhabitants descended with their herds into the valley every year, for grazing of the lands after the floods had receded, and that only later in history was the sowing of cereals practised.

The early stage: basin irrigation. The first to undertake the control of the Nile is said to have been Menes (3400 B.C.). A basin system of irrigation was gradually developed; the floodplain, which lay about 9 m above the riverbed, was divided into basins whose area varied from some 100 m² to several km². When the river flooded in July, August or September, feeder canals led water into the basins whose bottoms were then submerged to a depth of one metre or more. After the ground had become thoroughly soaked to the full depth of the root systems, the excess water was drained off – either into an adjacent basin downstream or into the bed of the subsiding river.

The annual flood brought with it some 100 million tons of suspended materials (Addison, 1961), and therefore usually left a thin layer of fertilizing material on the soil surface of the basin. The crop was sown as soon as possible, without any preliminary ploughing. Essentially, a single winter crop, mainly a cereal (barley or wheat), was sown each season, so that this was basically a subsistence economy (Hamdan, 1961). Other crops to be sown were pulses (beans and lentils), onions, and flax.

The basin system is technically a very primitive and expensive form of agriculture, similar in many respects to rainfed crop production on the semi-arid fringe of the desert. In both cases, only a single winter crop can be grown annually. On the other hand, the system showed a degree of permanency which is most rare for irrigated agriculture: the fertility of the soil and its productive capacity have been maintained under this system for thousands of years.

Several factors contributed to the biological soundness of the system: the thorough annual flushing of the soil, combined with excellent natural drainage, prevented salinization – the foremost problem of irrigated agriculture. The silt deposited annually provided plant nutrients in quantities that were adequate in view of the extensive form of cropping practised, thereby preventing soil exhaustion. The annual fallow period, which followed the harvesting of the cereal, took place during the hottest months of the year; the soil was thereby completely dried out, and as a result the weeds were destroyed and the population of pathogens in the soil was considerably reduced. Under this régime, the soil which had been packed by sowing, weeding, and harvesting operations, usually developed deep cracks whilst drying out, so that air was able to penetrate to a considerable depth and the soil structure was improved on rewetting.

The system was, however, not without its dangers. Successful cropping depended on the time of flooding and on its extent. If the flooding was too late, the growing season of the winter crops was shortened, with resultant reduced yields. If the flood was too low, the cultivable area was correspondingly reduced; if too high, the basins would be transformed into marshes and epidemics would occur. Hamdan (1961)

estimated that during the period from the 14th to the 18th centuries, no fewer than 50 plagues and major epidemics occurred in Egypt.

Nor was the basin system entirely free from the danger of salinization. Probably as a result of neglect of the canal network, normal drainage was hindered in the Berari region of the northern Delta, and some time in the late Roman and early Arab period over half-a-million hectares were lost to Egyptian agriculture following salinization (Hamdan, 1961).

Perennial irrigation. The basin system made possible subsistence farming only. Many cash crops, suited to the Egyptian climate, such as sugar cane, indigo, cotton, vegetables, and rice, require a regular water supply during the period from March to July, when the water level in the Nile is at its lowest and its flow is greatly reduced. These crops could be grown only by controlled irrigation lasting practically throughout the year. Such perennial irrigation also made it possible to grow more than a single crop annually.

The beginnings of perennial irrigation can be traced to the ponds and small lakes left behind after the floodwaters had retreated (Hurst, 1952). Summer crops could be grown in the neighbouring fields, and watered for many months after the flood, by using buckets filled by hand. Gradually, this method was replaced by primitive mechanical devices for lifting water.

A subsoil water reservoir, whose level ranges from 4–7 m below the surface, according to the time of the year, is fed underground from the Nile. This aquifer was tapped by wells, whose water complemented the river floods and made year-long irrigation possible. However, the water was not silt-laden, and the continuous cropping, made possible by this system, created serious problems of impaired soil fertility. Animal manure, and soil from long extinct settlements which was rich in phosphorus and potash, had to be applied regularly.

With perennial irrigation, a greater diversity of crops could be grown, and a more complex crop rotation established, than with basin irrigation. However, for perennial irrigation to achieve the scope required for growing food and export crops on a scale commensurate with the needs of a rapidly increasing population – from 2½ million at the beginning of the 19th century to about 7 million before the end of that century (Addison, 1961) – more effective and large-scale methods were required. Around the beginning of the 19th century, it was proposed to build a barrage on each of the two branches of the Nile to the north of Cairo, and thereby raise the water level in the river, so as to keep water flowing into the canals after the flood had receded. However, this first attempt to construct large-scale river control structures ended in failure. The necessary technical know-how was simply not available at the time, and the barrages that were constructed did not hold back the waters. A more modest and technically simple effort was more successful: an inundation canal – the Ibrahimie Canal – which diverted water from the Nile at Assiat, was dug some 320 km upstream from the Delta.

In the meantime, technical knowledge on the construction of barrages was increasing; by 1864 the Delta barrages had been strengthened and made serviceable and by 1902 a dam had been constructed at Aswan – the first of its kind in the world (Addison, 1961). This, together with a network of main carrier canals, branch canals, distributaries, and field ditches, made possible the perennial irrigation of two million hectares. In 1912, the Aswan Dam was made higher, and its capacity was more than doubled. Additional diversion barrages were also built – such as the Mohammed Ali Barrages, put in service in 1940, which replaced the by now obsolete Delta barrages.

With the expansion of the irrigated areas, certain dangers became manifest. The almost complete cessation of flow of the Nile into the sea increased the danger of seawater invading the Delta; to prevent this from happening, a special barrage was built and completed in 1952. Silting of the canals increased in amount and made it necessary to maintain an army of 400 000 men for four months out of each year to clear the canals. Perennial irrigation can also lead to a rapid rise in the water table, with resultant waterlogging and salinization of the soils. A network of drainage canals and ditches had to be developed in order to maintain the water table at an appropriate level and to remove excess salts.

The larger the areas under irrigation, the greater the danger of a catastrophe whenever the Nile flood does not reach its normal proportions. The first step taken to obviate this danger was to transform Lake Victoria at the headwaters of the Nile into an enormous storage reservoir, by controlling the flow from the Lake. The second step was aimed at reducing the considerable evaporation losses resulting from the sluggish flow of the Nile through the swamps in the Sudd region of southern Sudan. This was achieved by developing an artificial by-pass channel – the Jonglei Channel – which shortened and quickened the flow of the Nile waters through this region. The final step was the construction of the giant Aswan High Dam, about 110 m high above the riverbed, with a capacity of 130 milliard m³ of water (as compared with the former storage capacity of 5 milliard (Addison, 1961)).

In 1925, the ratio of perennial to basin irrigation in Egypt was 70%; by 1960 it had increased to 80%, the basins being confined to Upper Egypt (Hamdan, 1961).

Crops and cropping systems in Egypt

Under basin irrigation. In early times, barley was the principal crop and was gradually replaced by wheat. Pulses (including beans and lentils), as well as onions, were grown widely. Flax was also cultivated extensively, and provided the principal fibre for clothing.

Egypt has always been poor in pasture, and the number of domesticated animals has been relatively small. Therefore, for the livestock, and in particular draught and transport animals, forage crops have had to be grown, the most important of which is berseem (*Trifolium alexandrinum*). A two-course rotation is practised, with half of the area devoted to the cereal grain and the other half to assorted other crops.

Under perennial irrigation. With the beginnings of perennial irrigation it became possible to diversify cropping, especially by the addition of summer and perennial crops. Among the most important cash crops to be grown were sugarcane, rice, tobacco, and cotton – also the dye crops indigo and saffron, which were grown mainly in Middle Egypt. Egypt became an exporter of sugar in the 12th and 13th centuries, but this crop required heavy irrigation. Rice, also introduced in the Middle Ages, was grown on a large scale in the regions in which there was an abundance of easily lifted water. A perennial tree-type cotton, *Gossypium arboreum*, was grown on a small scale.

Cropping also became more intensive with perennial irrigation, and two or three crops could be produced annually. However, yields showed a tendency to decline, mainly as a result of impaired soil fertility. This resulted from several factors: the lack of silt in the irrigation water, the exhaustive cropping schedule, and the increased incidence of pests; also waterlogging and progressive salinization. In the clay soils of the delta, some of the best cotton soils lost their fertility in this way. The decline in fertility has been halted in recent times by very heavy fertilization with chemicals – mainly nitrogenous and phosphatic fertilizers – as well as by the establishment of an artificial drainage system. The relatively large area devoted to berseem in the crop rotation is also a major contribution to maintaining soil fertility.

At present a wide range of crops, including tropical, subtropical, and temperate crops, are grown. Not only have new crops been introduced, but traditional crops have been considerably expanded – though some of them, such as saffron and indigo, have practically disappeared, and others, such as flax, have declined considerably.

Cotton is the main crop, the old perennial types having been replaced by the high-quality, long-staple *Gossypium barbadense* of the New World. Maize, introduced relatively recently, has also become an important crop. Indeed maize, berseem, cotton, and wheat, together occupy 75% of the crop area, and are grown all over Egypt. Maize is the staple food of the fellah, berseem is the principal forage crop, and wheat is supplied to the town-dwellers. Cotton is, of course, the main cash crop, and is especially popular with the larger landowners. Cotton areas are limited by the necessities of crop rotation, but of every four or five crops that are grown in each two-year period, one is cotton (Addison, 1961).

Of the secondary crops, rice and sugarcane are increasing in importance, whilst beans and barley are declining. Relatively small areas are sown to lupins, lentils, fenugreek, chickpeas, onion, sesame, and groundnuts, which together account for about 3% of the cropped area (Hamdan, 1961). These secondary and minor crops are apt to be highly localized, being grown in certain specialized areas which have proven to be their optimum habitats. Thus sugarcane is concentrated in Upper Egypt, where the high temperatures are favourable to the crop, whilst flax is grown exclusively in the cooler and wetter north. Rice serves as a reclamation crop on salt-affected land, and hence is grown mainly in the northern half of the delta, which has the most severe salinization problems.

Irrigation water is not sold to farmers, but is delivered as a national service (Figs. 8.7 and 8.8). The taxable value of the land is assessed according to the irrigation facilities provided. The volume delivered to the individual farmer is in proportion to the amount of water in the river at a given time. For example, the extra water required for rice is supplied only if the Nile's flow exceeds a certain minimum figure (Addison, 1961).

Evolution of irrigation agriculture in Mesopotamia

The Tigris and Euphrates both originate in the snow-covered high mountains of Turkey, whilst the main tributaries of the Tigris (the Greater and Lesser Zab) have their origin in the highlands of Iran, which are also snow-covered. The Tigris–Euphrates basin lies mostly in the modern country of Iraq.

The origins of irrigation in the Tigris–Euphrates basin are obscure, but it is known that an elaborate system of canals was already in existence before 4000 B.C. Following the conquest of the valley of the Tigris and part of that of the Euphrates, Hammurabi established a strong, centralized government which exercised effective control over irrigation. Several of the laws of the Hammurabi code are concerned with irrigation, the land tenure system, and various other aspects of agricultural transactions.

The conditions prevailing in Mesopotamia for irrigated agriculture differ significantly in a number of ways from those of the Nile valley, and therefore the evolution



Fig. 8.7. Irrigating in Egypt with a metal 'sakiye' for lifting water, which largely replaces traditional wooden sakiyas, Archemides screws, and manually operated devices such as in Fig. 8.8. Photo D. Arnon, 1990.

of irrigated agriculture in the two regions, and their present-day situation, are entirely different – particularly in the following ways:

(1) The Tigris–Euphrates basin is in a dry steppe; a limited amount of rain-fed crop production is possible in the region. By contrast, the Nile flows largely in a desert, in which no crop production is possible without irrigation.

(2) The inundation by the Nile is regular and predictable. In Mesopotamia, floods occur in spring as a result of melting snows. The actual period of inundation is irregular, and cannot be forecast with accuracy. If the snows in the highlands melt too rapidly, destructive floods occur. The flood peak generally occurs late in spring and is therefore not well synchronized with the water requirements of the major crops. The floods recede about June, at the beginning of the hot season, so that a single flooding is not sufficient, especially as the principal winter crops – wheat,



Fig. 8.8. One of the many manually operated devices for lifting water from the Nile. Photo D. Arnon, 1990.

barley, and beans – are sown in November and December, and the peak requirements of the summer crops, such as cotton, sesame, and millet, occur after the floods have subsided. The floods are therefore always potentially dangerous and have to be kept in check. By contrast, the Nile flood reaches Egypt in late summer and early autumn, and the waters subside at exactly the right time for the sowing of the winter cereals.

(3) The Euphrates carries about five times as great a load of silt as the Nile (Whyte, 1961). The annual increment of silt has in due course raised the level of the riverbed, so that it is above the Plain. The Tigris, by contrast, has a deeply cut bed, with a very low water level, requiring barrages to make the water available for irrigation.

The heavy load of silt was not an unmixed blessing. It necessitated the constant clearing of the irrigation system, and raised the level of the fields. It is estimated that in the course of 5000 years, 10 m thickness of silt have been deposited in the fields (Jacobsen and Adams, 1958). As a result of this raising of the level of the fields, water has to be raised to a higher level for irrigation, causing a gradual reduction in the flow from the canals. The yearly deposition of silt therefore results in a decline in productivity, whilst the opposite was true in the deep-basin irrigation of Egypt (Gulhati and Smith, 1967). Meanwhile, in Mesopotamia, inadequate maintenance contributed to the siltation of river and canal beds, with a resultant reduced flow and reduced head of water.

After 1000–1500 years of successful irrigation agriculture during the Sumerian civilization, during which period most irrigation possibly consisted of uncontrolled flooding through breaches cut in the levees of the water courses, canal irrigation was introduced and a severe salinity problem began to develop, in addition to the difficulties caused by silting. The earliest and most serious manifestations were in southern Mesopotamia, and occurred about 2400–1700 B.C. (Jacobsen and Adams, 1958). The less salt-tolerant wheat was gradually replaced by more salt-resistant barley. By 1700 B.C., wheat cultivation had practically disappeared in the south, and the yields of barley had fallen considerably – from 2500 kg/ha prior to 2400 B.C., to 900 kg/ha by 1700 B.C. (*ibid.*). This latter figure is approximately the same yield as that obtained from rain-fed crops in the more favoured parts of the region. Whilst the region was not completely abandoned, it never regained its former prosperity. The great Sumerian cities declined into villages or fell into ruin, causing a breakdown of the Sumerian civilization.

Salinization was milder, and occurred later, in central and northern Mesopotamia; agriculture in these regions therefore continued to prosper. However, wave after wave of invasions took place, each resulting in a period of neglect, when parts of the irrigation system were allowed to go to ruin – to be followed by new upsurges of relative prosperity.

Devastation reached its peak during the Mongol invasions in the mid 13th century; during their occupation of the country, chaos prevailed, irrigation networks broke

down, and farming was not encouraged. Neglect continued during the Ottoman era. However, towards the end of Turkish rule, in 1913, the first barrage on the Euphrates, the Hindiye Barrage, was built. This was followed by the much larger Kut barrage on the Tigris, which was completed in 1939.

The large natural depressions which are characteristic of the plain were also used for diverting excess floodwater. They served the dual purpose of helping to keep the floods in check, and of creating reserves which could serve for regulating the water supply.

In 1959 the third and most important stage of development of the region was completed. The high dam across the Greater Zab at Dokan, built in a deep gorge, made it possible to impound 7 milliard m³ of water. At present, approximately three million hectares are irrigated in Iraq, half of them by gravity and half by lift irrigation (Addison, 1961). But the salinity problem over considerable areas is extreme and tending to heighten, to the detriment of agricultural productivity as a whole.

Irrigation agriculture in the New World

The beginnings of irrigated agriculture

Peru. Agriculture started on the central coast before 2500 B.C.; most authors agree that crops were probably grown on the floodplains, and possibly floodwater farming was practised. It is not until 400 B.C. that there is actual evidence of irrigation. Population pressure caused a rapid expansion of the areas under intensive irrigation. Inter-valley aqueducts were constructed to provide additional water for irrigation. The systems included structures for collection, transfer and distribution of water (Farrington, 1974).

Mexico. There is evidence of a water control system of outstanding proportions in the state of Chihuahua, that was built around the middle of the 11th century. A conservation system was developed in an area of more than 12 000 km² of uplands drained by the Casas Grande river; check dams were built in every arroyo to slow run-off, contour stone terraces slowed run-off from hillsides. The flow of the river was stabilized by these structures, and 80 000 ha of fertile bottom land were irrigated by an intricate system of canals (Herald, 1965).

Irrigation agriculture was already practised in prehistoric times in various parts of the American deserts by certain Indian tribes. At the time of the Spanish conquest, large diversion canals were already being used, in the Gila and Salt River Valleys of Arizona, to transport water to the fields – sometimes for distances of 30 km and more (Logan, 1961). These canals followed a regular gradient, though they had been built without any engineering instruments.

In the Rio Grande Valley, Pueblo Indians to this day practise an irrigation agriculture that is very similar in all respects to that practised before the advent of the White Man. Cultivation methods are primitive, yields are low, and the traditional crops –

maize, beans, squash, and melons – are produced. Meanwhile the Spanish missions had introduced Mediterranean crops and methods of irrigation, as well as potatoes and tomatoes from Mexico and Peru.

Modern irrigation schemes. The first large-scale attempts at irrigation agriculture in the desert by Anglo-Saxons were carried out by Mormons, who settled in the Great Salt Lake area of Utah. Religious motivation facilitated the establishment of a communal irrigation system. The Mormons introduced the crops of the northern temperate regions of Europe, with which they were familiar; these included wheat, barley, root crops, and forage and pasture crops, in addition to the typical European deciduous fruit trees.

At the beginning of the present century the so-called 'Reclamation Era' was initiated by President Theodore Roosevelt, which aimed at integrating flood control, power production, and water supply, for irrigation and other purposes. All the major streams of the west were harnessed, and it became possible to irrigate the enormous areas of hitherto unproductive land of the western desert. The Grand Coulee Dam in Washington, the Boulder Dam on the lower Colorado River, and the Shasta and Friant Dams of California, are some of the major projects involved.

In the warm-winter desert areas, such as the Imperial-Coachella Valley of California, with their long growing season and practically frostless winters, a vast array of crops can be produced; subtropical crops such as cotton and fruits such as dates and citrus, out-of-season vegetable crops as well as the typical temperate-climate crops such as wheat, barley, flax, etc.

In the cold-winter deserts, such as occur in Nevada, the choice of crops is much more limited, and the major emphasis is on the production of forage and pasture crops, which make possible a type of transhumance livestock industry. Cattle and sheep graze in summer at the higher altitudes, and on the irrigated pastures in autumn and early spring. In winter the animals are stabled and subsist on reserves of alfalfa hay. Other important crops of this area are sugar beets and celery, which are grown in summer.

Because the best lands for irrigation are usually in the lower-lying areas, where the soils are heavy and have little natural drainage, problems soon arise as a result of the raising of water tables and the accumulation of salts. Many of the irrigated areas are abandoned after a few years of intensive farming. Elsewhere, master drainage systems have had to be laid down, so that much of the irrigated land of the western desert area is now adequately drained. At present, further development of irrigation agriculture in the region is dependent on the exploitation of unconventional sources of water supply and on the large-scale diversion of water from the humid regions. Underground basins and streams are being exploited to the maximum (Logan, 1961).

In the Great Plains, the irrigated areas increased rapidly from the the 1950's, using water from the Ogallala Aquifer. In the 1980's, the total irrigated land area was over 3.6 million ha, or about the same as the irrigated area of California. In the Texas

High Plains, the area of irrigated land is equal to that of cultivated dryland (Johnson et al., 1983).

However, the fossil water of the Ogallala Aquifer is non-renewable, and it has been estimated that at the present rate of depletion the aquifer will be exhausted within 50 years, and the irrigated areas in the region will again become drylands (Gutentag et al., 1984).

Depletion is particularly critical in the southern portion of the Ogallala Aquifer area (Gutentag et al., 1984) where some of the previously irrigated land has been returned to dryland systems. In other cases, only limited amounts of irrigation water are used in various ways, ranging from preplant irrigation to application at critical growth stages (Stewart, 1989).

Potentials and problems of irrigation farming

Importance

The problems faced by many Third World Countries are daunting, and are becoming increasingly untractable. Agricultural production has declined, following cycles of drought, increasing population pressure on the land, compounded by a loss of export markets and the economic burden of a steep increase in food imports (Wyss and Petit, 1990).

Irrigation development therefore appears to be the only long-term effective solution to the food problems of the periodically drought-stricken areas of the world.

Irrigation is also considered to be the first essential step in the development of the *dry regions*, and a powerful tool for progress in *semi-arid regions*, in which rainfed cropping is practised. Irrigation makes possible a more intensive succession of crops, higher yield levels and a greater diversity of crops than rainfed production. Wheat yields under irrigation are three- to fourfold those obtained from dryland production.

The development of irrigation also has an impact on the development of non-agricultural sectors of the economy, such as commerce, services, and transportation; it contributes to the balance of payments and provides a market for local industrial production of agricultural equipment and inputs.

Only about 10% of the world's cultivated area is irrigated. A number of countries are, however, heavily dependent on irrigation; e.g. Egypt, where the whole cultivated area is irrigated, Peru (34%), Japan (67%), Iraq (32%), Mexico (22%), and Pakistan (70%) (FAO, 1984).

Lack of success of many irrigation projects

Some large-scale public irrigation projects "perform exceptionally well" (Seckler, 1990), but many others have very poor records. Almost all the large irrigation schemes in Sub-Saharan Africa are experiencing some difficulty with management

and operation, so that irrigation is considered to be a risky investment (Le Moigne and Barghouti, 1990).

Investment in irrigation projects in Asia, Latin America and Africa increased rapidly after World War II. "Water supply decisions have largely been made in the political arena rather than in the market place, and this to exploit public romanticism – for making the desert bloom" (Clark, 1970).

Most irrigation projects are concerned with major irrigation structures: diversion dams, storage reservoirs, canals, etc. These provide water, but without a coordinated development plan for the conservation of the watershed above the project, the provision of drainage and the necessary infrastructures, as well as the inputs required for the effective use of the water, these projects cannot be fully productive.

Unfortunately, some of these aspects are frequently neglected. The *authorities* are concerned mainly with the prestige derived from spectacular large-scale structures and the *irrigation engineers*, who are concerned exclusively with diversion, storage and conveyance of water, usually have little understanding of the effective application and use of the water on the individual farm (US President's Science Advisory Committee, 1967).

The majority of the countries introducing irrigation, especially in the developing countries, still continue to make fundamental errors in planning and implementing irrigation projects. (Kovda, 1977).

Reasons for shortcomings and failures. Most of the shortcomings and failures of public irrigation schemes are common to most projects. The factors involved are mainly technical, institutional and economic:

Technical.

(a) They disregard the implications of the natural soil situation in each country, the level and quality of the irrigation water, the salinity of the soil up to the ground-water table and the conditions of natural drainage.

(b) They neglect to install deep drainage in order to reduce costs of development.

(c) They effect excessive application of water (Kovda, 1977).

Lack of provision of technical and financial assistance for field levelling and field drainage was responsible for disappointing results of irrigation schemes in Iraq (Stippler and Darwish, 1966).

Institutional. Six institutional bottlenecks in the Near East prevented the full impact of irrigation schemes on agricultural production (FAO, 1962). These were:

(a) Lack of incentive to investment as a result of the agrarian structure and systems of land tenure.

(b) Shortage of institutional credit. More than 85% of all farm credit was provided by moneylenders who charged exorbitant interest. Farmers had to sell their products immediately after harvest at prices dictated by their creditors.

(c) Inadequate supplies of fertilizers, insecticides, etc. Supplies were either not

available locally or at the right time, or not in sufficient quantities or at reasonable prices.

(d) Poor marketing facilities, lack of storage, and no effective guaranteed prices for basic commodities.

(e) Inadequate extension service: the ratio was 1 extension worker to 8000 farmers, in contrast to a minimum desirable level of 1 to 1000. Standards for training of extension workers were also unsatisfactory.

(f) Absence or inadequacy of farmers' organizations.

Institutional factors are responsible for deteriorating maintenance and declining output from African large-scale public irrigation schemes (Le Moigne and Barghouti, 1990).

Economic. Large projects require large capital outlays, frequently have cost overruns, lower than expected rates of return, and a slow uptake by farmers.

Long construction delays and cost overruns are a frequent cause of reduced rates of economic return. These have generally been caused by "poor surveys, inadequate preparation, unrealistic assessments of benefits, and the lack of systematic planning and administration" (Le Moigne and Barghouti, 1990). In Nigeria, for example, between 1973 and 1984, about 40% of the government agricultural expenditure was invested in developing 30 000 ha of land for irrigation, at a cost of approximately 100 000 US\$/ha (Lele and Subramanian, 1990).

Policy. The policy environment is frequently unfavourable to implementation of irrigation projects. Availability of inputs, adequate budgetary resources, accessible markets, reasonable costs of inputs and prices of the commodities produced are often neglected. High taxes and unrealistic exchange rates, high transport costs inflate costs of development and implementation (Le Moigne and Barghouti, 1990).

National planners are strongly attracted to irrigation as a means of supporting food strategies wherever rainfall is deficient or erratic, and demographic pressure on rain-fed land is increasing; however, some politicians are prepared to sacrifice long-term national interests for immediate sectorial interests.

In Nigeria, small-scale, private irrigation has been far more successful (cf. p. 393) than large-scale public irrigation projects. "The record of achievement had done little to shift the emphasis from the mainstream large-scale irrigation strategy in force" (Lele and Subramanian, 1990). The main reason is the desire and intention to maintain the distribution of patronage that large-scale, centralized projects make possible. Politically powerful domestic and foreign interests that benefit from the construction of large-scale projects are also involved (ibid).

On-the-farm problems. Irrigation agriculture *can* be the most productive form of farming, but it would be a great fallacy to suppose that irrigation, as such, is equivalent to intensive agriculture and capable of increasing productivity and raising the standard of living if applied in a primitive way. Actually, in many countries, irrigated agriculture is still the epitome of backward methods of production.

Because of its high capital and operating costs, irrigation agriculture must be intensive. Successful irrigation involves far more than applying water to the land; it becomes an effective tool for increased production, maintained on a high level, only when applied in conjunction with appropriate changes in crops and varieties and employment of the most intensive and up-to-date cultural practices, ensuring high yields per unit of water.

There is a general agreement, among both Indian and foreign experts, that disappointing results from irrigation projects in India were due to the lack of relation between water inputs and other inputs, and the lack of effective coordination between the departments of irrigation, of agriculture and of agrarian reform. A contributing factor was the inappropriate size of land holdings. However, the main reason was that areas under irrigation were increased without concern for intensification of production methods.

Consequences. As a result of the foregoing, many irrigation schemes in East Africa have either failed outright or have operated over a long period of time without recovering their costs (Chambers and Moris, 1973). Kenya has promoted large-scale irrigation with very limited success. The worst case was the Burra Irrigation Project which was developed between 1977 and 1988 (Lele and Subramanian, 1990). The World Bank (1988) in its 'Project Completion Report' states that: "the Burra Project did not contribute to the objective, expressed at appraisal, of developing Kenya's capacity to manage future major irrigation projects. On the contrary, the experience discredited development of irrigation as a tool to achieve agricultural growth and employment".

Lele and Subramanian (1990) further point out that there were many signs at the appraisal stage that the Burra Project was not a sound proposition. Soil suitability was problematic, and problems of soil salinity, high sodium content and low subsoil permeability were identified in the project evaluation studies.

Many of the drawbacks and failures of irrigation schemes are common to all types of settlement schemes. As a result, irrigation efficiencies in developing countries are extremely low: it is estimated that only 40% of the diverted water actually reaches the field, and this is used with an irrigation efficiency of 30 to 40% at the best – so that an effective utilization of water of only 10 to 20% is by no means uncommon (Garbrecht, 1979) and the productivity of water bears little relationship to its cost (Crosson, 1975).

A typical example of inadequate results from irrigation is that of the Plain of the Punjab and Sind regions of West Pakistan, which is watered by the Indus and its five tributaries, carrying more than double the flow of the Nile. In this region, more than 70% of the population of 30 million people live from farming, and produce food and fibre for a total of 50 million people. Only half of the flow of the rivers is used to irrigate about 9 million ha – the largest single irrigated area in the world. The under-

ground aquifer contains an amount of fresh water that is estimated to be ten times the annual flow of the rivers (Revelle, 1966).

In spite of this enormous potential for developing a prosperous agriculture, the majority of the population lives in poverty, and food has to be imported into the region. This is the result of poor drainage, that has caused waterlogging and salt accumulation, and of problems of land tenure and poor farming practices. About one-fifth of the area is already damaged by salinity and waterlogging. The canals lose so much water by seepage that the actual amount delivered into the fields is sufficient to irrigate only half of the land during each season. The shortage of water causes a tendency to under-irrigate in summer, acerbating salinity problems. The situation is further aggravated by primitive cultivation methods, the use of unselected seeds of low-yielding varieties and inadequate fertilization.

Similar problems exist in the valley of the Tigris–Euphrates, albeit on a smaller scale. It is estimated that with adequate leaching and drainage, the adoption of multiple cropping and better farming practices, including the use of fertilizers, total agricultural production could be increased at least fivefold in these two regions (Revelle, 1966).

Small-scale irrigation projects

Large-scale public irrigation projects have certain inherent drawbacks: they require large capital outlays, a complex infrastructure, considerable expertise in irrigation engineering and technology, a large distribution network and complex management (Elahl and Khushalani, 1990).

Chambers and Moris (1973), writing on the problems encountered in large public irrigation schemes state: “in general, the larger the project is, the higher the cost, the larger the number of people involved, and the more publicity it receives. The risks are not simply that such a project will fail, but that having by all normal economic criteria failed, it will remain a permanent millstone weighing down the national economy”.

By contrast, small-scale schemes have certain advantages: greater local involvement, increased mobilization of local capital savings, reduced needs for administrative and managerial expertise, faster development and utilization, and more appropriateness for small landowners. Indeed, small-scale projects have generally had a better record of success than large, state-operated projects (Elahl and Kushalani, 1990).

In communist China, during the earlier years of the regime, many large water conservation projects “were carried out with great enthusiasm and fanfare. It soon became evident that many of the projects did not perform as satisfactorily as expected”. Subsequently, emphasis was given to small and medium-sized projects, such as digging of wells and ponds, construction of dikes, ditches, reservoirs and embank-

ments, and harnessing of small rivers. The intention was to form, gradually, coordinated networks (Kuo, 1972).

In Iran, a review of previous agricultural development plans led to a change in emphasis to encourage small irrigation schemes rather than the large-scale river development projects that had been favoured previously. This shift to small schemes made it possible for the Iranians to administer these irrigation schemes themselves and so lessened their dependence on foreign experts (Gittinger, 1965).

The potential for smallholder irrigation in Africa south of the Sahara has not been sufficiently exploited. Whilst floodplain cultivation of river banks and shorelines of lakes is quite common, little effort has as yet been made to dig wells, even where the water table is sufficiently close to the surface. For example, in the Casamance area of Senegal, lowland rice is cultivated only during the rainy season; the water table is less than two metres from the surface and it would be possible to grow another crop during the dry season, when farmers have little work, if this potential for irrigation was effectively used (Eicher et al., 1970).

Where objective circumstances dictate the need for large-scale projects, the small irrigation schemes can serve as pilot projects, providing a low-cost opportunity to gain experience in irrigation practice, agrotechniques, choice of crops, etc., as well as to provide training for technical personnel and farmers (Elahl and Khushalani, 1990).

Environmental impact

The cost and benefits of irrigation projects cannot be considered exclusively in financial terms. Irrigation development involves considerable potential and actual environmental costs: waterlogging, salinization, damage to water supplies downstream, and – probably the most devastating effect – the development of water-borne and water-related diseases (Olivares, 1990).

The environmental impact of irrigation will be addressed in detail in Ch. 13.

Preconditions for success

Seckler (1990) states that at least six environmental conditions have to be met for irrigation projects to succeed: economic justification; an adequate supply of good quality water and suitable land within reasonable proximity of each other; reliable and economic availability of yield-increasing inputs (quality seeds, fertilizers, agrochemicals, etc.) and labour; accessible market(s); reliable transportation system; equitable and stable input/output prices.

Le Moigne and Barghouti (1990) make the following recommendations: the data base should be improved, especially in relation to the country's water resources; existing projects should be rehabilitated and modernized; high priority should be given to expanding small-scale irrigation projects; new technologies should be pilot-tested before large-scale adoption; improved cultivation methods should be an integral part of irrigation technology; research should be expanded on the development

and improvement of irrigation, on water usage, on high-yielding varieties and high-value crops, as well as on marketing and organization. Environmental and social factors should not be neglected.

Lele and Subramanian (1990) conclude from the African experience that the central lesson to be drawn is that investment in irrigation cannot succeed without a carefully formulated strategy that includes “an assessment of soil and water potential, and of the technologies to be used for mobilizing and delivering water and in crop production. Most important, it must insist on a review of the institutional capacity and human capital available to handle investments and operations most efficiently”.

Recapitulation

Throughout the historical period, certain traditional patterns of land use have evolved that characterize subsistence agriculture in dry regions in various parts of the world. These patterns are extraordinarily similar over wide areas, despite the great diversity of habitats due to various combinations of soil and topography within a climatic region. This similarity is encountered despite the fact that the land use patterns developed independently on various continents.

Furthermore, the traditional land use patterns have shown a surprising amount of stability, having remained unchanged in subsistence agriculture throughout the historical period, and even to the present day. Change has occurred only when the traditional farming systems were undermined by external factors, the principal one being population pressure, or, alternatively, modified by the introduction of modern methods and inputs.

The arid regions

Nomadism and transhumant pastoralism are very ancient natural adaptations to the sparse vegetation, seasonal growth of forage, and drying up of watering places that are characteristic of arid lands; they are therefore the traditional forms of land use of enormous desert tracts in the world.

The grazing lands of the dry regions are an important economic asset of the developing countries of these regions. This natural resource is generally both neglected and abused, mostly as a result of overpopulation and overstocking. The results are low productivity of pasture and livestock, widespread erosion and desertification, and an extremely low standard of living.

These drawbacks can only be overcome if a coordinated improvement programme is adopted incorporating (a) an agronomic approach, whereby the range is improved by brush control, re-seeding and fertilization, and grazing management; (b) the creation of forage reserves; (c) improved livestock productivity through breeding, proper

management, disease and pest control, adequate livestock handling facilities and all-season, strategically placed watering points; and (d) appropriate government planning, strategy and implementation of development plans and adequate aid to pastoralists. It is essential to reduce population pressure on these lands; therefore, for a large number of pastoralists and their dependents, there appears to be no alternative to their adapting to a sedentary life.

Ranching, i.e., a highly commercialized and specialized approach to improving animal production in drylands, requires high capital investment, enormous areas per unit of production, and expert management to provide a high income to the ranchers. It is widely used in the developed countries with extensive rangelands for which irrigation is not feasible.

Early research on the potentials of domestication of plants adapted to desert conditions did not give promising results, but a renewed interest in this topic may possibly result in more optimistic assessments.

Rainfed farming in the semi-arid regions

The semi-arid regions include Mediterranean-type climates with winter rainfall, subtropical climates with summer rainfall, and middle-latitude climates, with predominantly summer rainfall and part of the precipitation in the form of snow.

Cereal cultivation is the main source of livelihood: wheat and barley in the winter-rainfall areas; maize, sorghum and millets in the tropical summer-rainfall areas, small grains, maize and sorghum in the middle-latitude zones.

Crop rotation, integrated animal husbandry and arable cropping, appropriate soil and water conservation practices, the use of improved varieties in conjunction with fertilizer application and crop protection, have made it possible to use the available precipitation most efficiently, while preventing damage to the land by run-off and erosion. The result has been a dramatic increase in production in these areas.

It is in the marginal-rainfall areas that the transition from grazing to arable cropping, generally under increased population pressure, is most dangerous, and may have catastrophic results, mainly through wind erosion.

Irrigation agriculture

Different forms of flood irrigation and water harvesting may provide a viable solution for dry regions in which no other sources of water supply are available.

Conventional irrigation can be a powerful tool for agricultural development, not only in the arid areas, but also where rainfed farming is possible. The development of irrigation can have considerable impact on the development of non-agricultural sectors of the economy.

However, whilst irrigation agriculture can be the most productive form of farming, disappointing long-term results have been obtained in a large number of irrigation

projects in developing countries, mainly because of fundamental errors in planning and implementation.

The advantages of small-scale projects, in which water resources are developed at the level of the individual farm or village, are increasingly being appreciated. Their cost per hectare is far lower than in the large irrigation projects, a greater proportion of the work can be carried out by the beneficiaries themselves and allocation of water is easier. Consequently, the rate of success is far greater.

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CHAPTER 9

Sustainable Agriculture in Dry Regions

The deterioration of natural resources

The problem and its importance

Agricultural production is by its nature an extractive process; it is, however, only in relatively recent times that the realization has crystallized that appropriate measures have to be taken if agricultural resources are not to be irrevocably destroyed by negligent use of land and water by man.

Agricultural development increases the potential for resource deterioration and even destruction. The construction of reservoirs, the development of irrigation projects, mechanization and the use of chemicals for increased production or plant protection react with the environment in a number of ways that may have disruptive effects.

In most countries of the world, but especially in the tropics and subtropics, enormous areas of land have been damaged by clearing of forests, erosion, salinization and sodication, and by desertification.

Buringh (1978) estimates the areas lost to cultivation annually as approximately five million hectares (ten hectares every minute!), of which 50% are ascribed to erosion, 30% to salinization and 20% to desertification and degradation. Other estimates of these losses are much greater still.

In addition, the growth of the infrastructure of transport and communication, increasing urbanization and the development of industry (all of which are concomitant with rural development) have consequences for the ecological system (United Nations, 1971). According to UN estimates about 630 million people (roughly 16% of the world's population) live on arid or semi-arid lands. About 78 million of these people live on lands almost completely degraded by erosion, sand dune formation or salinization; 70% of these people depend on agriculture alone on these degraded lands. Areas assessed as being high or very high risk occupy most of the arid and semi-arid regions and extend into adjacent subhumid regions. Neglecting the very cold drylands and the extreme deserts there remains an area of potentially productive

but threatened drylands covering 45 million km² or 30% of the world's land surface. These occur so widely that two thirds of the 150 nations of the world are affected. Desertification is therefore a world problem. The annual rate of desertification is estimated at six million ha (Ramana, 1980).

Land degradation

Causes

The principal causes of degradation of natural resources are: degradation of vegetative cover, water and wind erosion, salinization, mismanagement of the soil, excessive exploitation of groundwater resources, pollution by injudicious use of chemicals, population pressure, and urbanization.

Land degradation involves a continuous decline in productivity as a result of the impoverishment and depletion of the vegetative cover, exposure of the soil to wind and water erosion, reduction of the soil's organic and nutrient content, and deterioration of the soil structure and capacity to retain water.

Part of this decline can be attributed to the high rates of population growth, periodic droughts, and unfavourable agricultural and marketing policies of the national governments; much of it results from the steady and continuing degradation of agricultural lands due to soil erosion and nutrient depletion and the subsequent loss of soil productivity (FAO, 1986).

The potential for degradation of land is greatest in the dry regions of the world; the ecosystem is very fragile, and as temperatures increase and precipitation decreases, soil erosion and accelerated loss of organic matter become the dominant degradative processes (Parr et al., 1990).

Soil degradation includes (Lal et al., 1988):

- *physical deterioration* such as compaction and destruction of soil structure, laterization and erosion;
- *chemical deterioration* due to leaching, acidification, salinization and alkalization; insufficiency of essential nutrients or excessive concentrations of toxic elements;
- *biological deterioration* resulting from reduced activity and diversity of soil macro- and micro-organisms and from decreases in quantity and quality of soil organic matter (Riquier, 1982).

Generally, the most serious degradative processes in vast arid and semi-arid zones are soil erosion, and associated nutrient losses, as well as losses of organic matter (Parr et al., 1990).

Soil erosion

Economic development depends, in the last analysis, on the proper use and conserva-

tion of the soil. Population pressure, destructive tillage methods, faulty irrigation practice and overgrazing can cause the deterioration of the soil, and this is frequently an irreversible process.

Erosion per se is a *natural process* contributing to soil formation by wearing down mountains and building up the soil in more level lands. Proceeding at a slow pace, it may, therefore, be very beneficial. However, it becomes a catastrophic process when it is excessively accelerated by man.

Factors for accelerated erosion

The main factors for accelerated erosion in the course of the last century are:

- (a) The ploughing up of farmland, in marginal semi-arid regions, which is generally conducive to wind erosion. The classical example is, of course, the creation of the dust bowl in the 1930's in the dry, central parts of the United States.
- (b) The destruction of vegetative cover on slopes, in particular in the humid regions, leading mainly to water erosion. This is generally the direct result of population pressure causing a shortening of the fallow period in shifting cultivation, and overgrazing in pastoral agriculture.
- (c) Incorrect tillage methods (e.g., ploughing down the slope), usually as the result of excessive parcellation between heirs in successive generations.

The semi-arid areas are especially susceptible: a protective vegetative cover between crops is either impossible or unacceptable because (a) the considerable water consumption involved, (b) limited moisture, and (c) crops frequently provide sparse cover and leave little residue (Henderson, 1979).

Impacts

Soil erosion is frequently the culmination of a process that begins with the loss of soil fertility and impaired soil structure (Fig. 9.1). Soil erosion in turn further reduces soil fertility by selectively removing the smallest and lightest particles, thereby reducing the proportion of soil colloids and increasing that of the large, inert particles of sand. Thus a vicious circle is created, whereby the fertile top soil is gradually removed, leaving the far less fertile subsoil exposed. The subsoil being relatively compact, water infiltration into it is slow and limited. Tillage becomes more difficult and less efficient. Biological activities in the soil are slowed down, as a result of impaired soil structure and deficiencies of available nutrients. Even long after the addition of fertilizers and manures, the subsoil remains less fertile than the top soil that was removed by erosion.

The subsoil in turn is even more susceptible to erosion than the top soil, because of its poor structure and low organic-matter content. Run-off increases, gullyng results, and the field may soon be in a condition which makes cultivation uneconomical.

The damage is not confined to the eroded fields. Both wind and water transport the

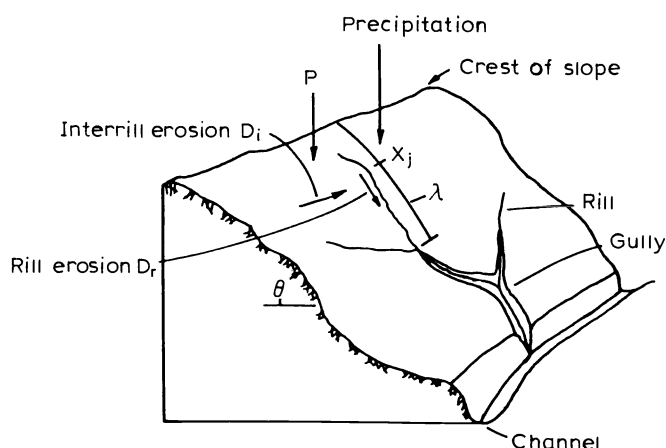


Fig. 9.1. Schematic presentation of erosion on interrill areas, rills, gullies and channels. From Renard and Foster (1983). By permission of the American Society of Agronomy, Inc., the Crop Science Society of America, Inc., and the Soil Science Society of America, Inc.

eroded soil selectively: the first to be deposited are the coarse sandy particles, which may cover to a great depth fields that were previously fertile, whilst the light fertile particles remain in suspension for great distances, and usually end up in the desert (loess soils) or in the oceans.

In a review by ASAE (1985) on the relation between erosion and soil fertility, nearly all research results showed a significant impact of soil erosion on productivity. In some cases, decline in crop yields was rapid, in others, yields were reduced significantly over a long period of time.

Besides impairing the fertility of cultivated soils, soil erosion is a major factor in environmental pollution. Residues of agro-chemicals, such as fertilizers, pesticides, and herbicides, are generally associated with the finer soil particles that are the most readily transported by wind and water. The discharge of considerable amounts of silt into river systems causes the accelerated filling up of reservoirs and increases danger of floods; the sediment is also the major carrier of the chemical pollutants mentioned before.

Much land formerly under cultivation has been abandoned owing to soil erosion, which is widespread in many developing countries. South America has been called the 'vanishing continent'. It is estimated that a quarter of the total land under cultivation, past and present, has lost its top soil through erosion (Benham and Holley, 1960). A survey of soil of erosion in Chile, on 1 200 000 ha, for example, showed that only 12.6% was not affected, whilst 40% had been badly damaged (Pawley, 1963).

All the destructive processes of soil erosion tend to increase when marginal areas of low rainfall are cultivated for field crops. Though annual rainfall is low, very high



Fig. 9.2. Effect of a single rainstorm on a bare cultivated field with only a slight slope. Photo Soil Conservation Service, Israel.

intensities occur, and combined with the poor plant cover, result in increased erosion losses.

The ploughing of great areas of grassland for wheat and maize cultivation in Argentina has caused wind erosion on a large scale and has brought about a situation very similar to that of the dust bowl in the United States (Benham and Holley, 1960).

In the Sahel zone of West Africa recent droughts, overgrazing and destruction of trees and shrubs used for firewood have accelerated erosion by wind in the dry season, and by water in the rainy season (Cannell and Weeks, 1979). In other parts of semi-arid Africa, in which shifting cultivation is the dominant form of land use, population pressure has caused a shortening of the fallow period which no longer permits the regeneration of the vegetative cover, leading to erosion on a catastrophic scale (cf. p. 365).

Erosion by water (Figs. 9.1 and 9.2)

Erosion prediction. Erosion prediction has progressed from data collection and experimentation comparing practices, to simple models, then to complex empirical models, and most recently toward process-based models (McCool and Renard, 1990).

The most widely used empirical model in use is the Universal Soil Loss Equation, developed by Wischmeier and Smith (1960) for predicting soil losses due to water erosion:

$$A = R \times K \times C \times L \times S \times P,$$

in which A is the average annual loss of soil in t/ha; R is a rainfall run-off factor; K is a soil erodibility factor, C is a crop management or plant cover factor; L and S are factors for slope length and slope steepness, respectively, and P is a soil conservation practice factor.

The R factor is based on rainfall records for the location concerned; likewise the K , C , L , and S factors are specific for a given location. The C or crop management factor can be altered for achieving optimal erosion control. When management practices alone cannot effectively control erosion, engineering-type control measures may be essential (Unger, 1990).

The equation is generally used with a value, T , which is the maximum allowable soil loss considered safe for maintaining long-term productivity of the soil. This tolerance level usually ranges from 6.7 to 11.2 t/ha, depending on soil type (Larson et al., 1978).

Current soil conservation programmes are based on reducing soil erosion to a 'tolerable' level, defined by the Universal Soil Loss Equation (Keeney, 1990). It can be argued that many agricultural regions cannot afford to lose soil at all, and that soil loss should be held essentially to zero.

Factors influencing water erosion. Rainfall. The semi-arid regions are characterized by the occurrence of intense rainstorms that cause the breakdown of soil structure, seal the soil surface and cause excessive splash erosion and destructive water run-off.

Vegetation. In most arid areas, the C factor is the most important term in the equation because it varies as a function of cover (Fauck, 1977). In the semi-arid areas, the natural vegetation has, in the past, generally been sufficient to afford adequate protection against erosion. The vegetative cover reduces the amount of rain that impacts directly on the soil and the kinetic energy of the raindrops.

The destruction of this protective cover by ill-advised agricultural activities has resulted in the loss of soil from enormous areas, both in developing and developed countries.

Slope. This is also a major factor in soil erosion by water. Slopes greater than 10% should not be cultivated, unless terraced. On concave slopes, soil is deposited in the lower part of the slope; on convex slopes there is no soil deposition (Cannell and Weeks, 1979).

Soil texture and structure. Clay mineral particles are better able to resist removal than sand particles, because of the attractive charges of the former; however, once detached, clay particles are more easily transported than large-grained sand. Soils

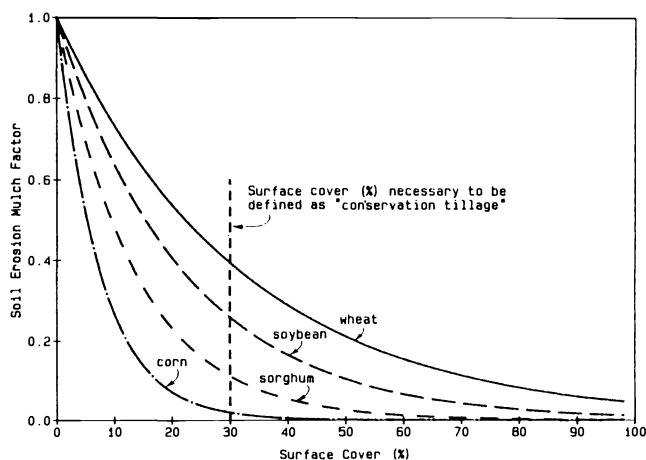


Fig. 9.3. The relationship between soil erosion mulch factor (SEMF) and surface cover for wheat, soybean, sorghum, and maize residues. A soil with no residue receives a SEMF of 1.0. A field with a SEMF of 0.1 would experience only 10% as much soil erosion as the field without residue cover. At the level defined as conservation tillage (30% surface cover), the soil erosion mulch factor varies from 0.4 for wheat to less than 0.1 for maize. From Colvin and Gilley (1987). By permission of the American Society of Agronomy, Inc., the Crop Science Society of America, Inc., and the Soil Science Society of America, Inc.

with a stable structure (cf. Ch. 10) tend to resist erosion; breakdown of structure reduces infiltration of water and thereby results in increased run-off.

Control. Research results and practical experience from a range of soils and climatic environments have confirmed that the most effective erosion control measure is good soil and crop management (Unger, 1990).

A major conclusion from long-term studies on soil erosion is that the most important factor in erosion control on cultivated fields is the degree of surface protection provided by crops or their residues, and surface roughness (Cannell and Weeks, 1979).

A complete cover of surface residues provides the maximum protection against erosion (Unger, 1990). The mulch also increases water infiltration and minimizes run-off. The relationship between soil erosion and soil cover is shown in Fig. 9.3.

A vegetative cover should be maintained through appropriate cropping sequences, mixed and relayed cropping, strip cropping, and promoting rapid growth. Soil management practices should aim at maintaining and improving soil structure.

Tillage operations should be reduced to the minimum possible (cf. Ch. 14) and carried out on the contour. A no-tillage system can control run-off and erosion on slopes of up to 15%; with this system it is often unnecessary to use other control measures, such as terraces and diversion channels, provided there are sufficient quantities of residue mulch (Lal, 1984).

Engineering practices, such as the construction of terraces, can be very effective, but require heavy initial investment that is beyond the means of the small farmer. Moreover, mechanical structures may fail if they are not properly constructed and maintained, and may then become actual erosion hazards.

Erosion control has to be planned and implemented on a watershed basis, and this is clearly a government responsibility.

Paradoxically, a conflict of interests may result from soil conservation measures: the more effective the fight against erosion in the upper reaches of the watershed, the greater is the reduction in run-off and the lower the amounts of water that reach reservoirs downstream. Thus, control of grazing to preserve a grass cover was effective in preventing excessive trampling and soil exposure and in reducing soil erosion but also resulted in a reduced water flow from the area.*

The investment in effort required for effective soil erosion prevention measures may be quite considerable and the visible effects of erosion are generally long-term, whilst the beneficial effects of many of the measures proposed are still less visible in the short term. It has therefore frequently been difficult or even impossible to obtain the willing cooperation of farmers in the execution of soil conservation projects.

The high cost of engineering structures, and the inconvenience caused by terracing and ploughing on the contour are also major deterrents, especially in semi-arid areas, with their relatively low and uncertain economic returns.

Faced by these difficulties, governments in some developing countries have attempted to enforce control measures by decree, with extremely negative results.

In the light of these constraints, Henderson (1979) concludes that acceptable control practices "must be relatively simple and require little or no sacrifice in yield". Conservation tillage is the nearest approach to meeting this requirement (see Ch. 14).

Erosion by wind

Although wind has a much lower soil transport capacity than water, its impact is more far-reaching: water erosion is restricted to sloping land, while wind can remove the most fertile particles from the entire soil surface (Fryrear, 1990).

Many arid areas, especially those with sandy, unaggregated soils and sparse vegetation, have a high potential for wind erosion. Equally vulnerable are semi-arid areas from which the natural vegetative cover has been destroyed.

Factors influencing wind erosion. Conditions that favour wind erosion are: a loose, dry soil; a smooth soil surface with little or no cover; large field and a strong enough wind to move soil (Skidmore and Siddoway, 1978).

*For a detailed treatment of the subject, the reader is referred to a publication by the FAO (1977), and FAO/UNEP (1983).

A wind erosion equation was developed by Woodruff and Siddoway (1965) which shows the relationship between average annual soil loss and five factors influencing wind erosion:

$$E = f(I', K', C', L', V').$$

E is the amount of annual soil loss in t/ha and is a function of: I' , a soil erodibility index which depends on the proportion of soil aggregates >0.84 mm diameter and the slope of the surface; K' , the soil surface roughness; C' , the climatic factor depending on wind velocity and surface soil moisture; L' , the unsheltered field length along the direction of the prevailing wind; and V' , the vegetative cover.

The mathematical relationships are complex, but have been computed and developed into tables that provide the values required for estimating soil losses from the equation for specific conditions (Woodruff et al., 1972).

Processes of wind erosion. Erosion begins at relatively low wind speed and increases progressively as wind speed and turbulence increase.

Dust particles are moved by wind by three processes: saltation, suspension, and surface creep (Bagnold, 1954).

Saltation: soil particles are lifted by the wind and move into the mainstream of the air; gravity pulls the particles to the soil surface where they strike other particles and rebound to continue moving forward.

Suspension: very fine particles (dust) are lifted from the soil surface by the impact of saltating particles, and are carried aloft by vertical currents or upward eddies. Dust remains in suspension in the air and may be carried for considerable distances.

Surface creep: very large particles, too heavy to be lifted by the wind, move forward by surface creep.

A severe and prolonged drought, by reducing the vegetative cover, can increase the destructive effect of winds. During the drought of the 1930's in the Great Plains of the USA and in the 1970's in the Sahel of Africa, one severe wind could remove 10 cm or more of top soil from a field in a few hours (Bowden, 1979).

Control methods. To minimize wind erosion, wind speed at the soil surface must be reduced below the threshold value at which erosion occurs (Skidmore and Siddoway, 1978).

Many of the control measures adopted for erosion control by water are also effective against wind erosion. More specific are those methods designed to reduce wind velocities near the soil surface. Roughness of the soil surface, due to the presence of clods, ridges, depressions, vegetation and crop residues can make a significant contribution to wind erosion control.

The stubble mulch tillage system was mainly designed to control wind erosion after the dust storms that devastated large areas in the semi-arid regions of the USA in the 1930's, resulting in the 'dust bowl' (cf. p. 372). Additional management practices

include minimum tillage, crop rotations designed to provide adequate year-round vegetative cover, strip cropping, and controlled grazing (Cannell and Weeks, 1979). Most effective is no-tillage, because the residues are anchored in the soil (Unger, 1990). These subjects are treated in detail in Ch. 14.

Increasing the clay content of sandy soils is used as a control measure on large areas in the southern Great Plains of the USA. The clay is brought to the soil surface by deep-ploughing (cf. Ch. 14) sandy soils with a higher clay content in the subsurface profile (Fryrear, 1990). Similar results can be achieved where the sand layer covers loessial deposits.

The most effective way to control wind erosion is by using an appropriate combination of various control measures (Fryrear, 1990).

Wind erosion in desert areas can be checked first and foremost by preventing degradation of the vegetative cover; if the land has already been denuded due to overgrazing, restoration of a plant cover is the first essential step (cf. p. 353). Wind erosion can be significantly reduced by establishing windbreaks and by stabilizing sandy areas and dunes with adapted grasses and shrubs.

Windbreaks or shelter belts. Advantages. The use of trees, shrubs and other protective devices to provide shelter against winds is a wide-spread practice. Their advantage over other methods of wind erosion control is their relative permanency. During a series of drought years, shelter belts may be the only effective and persistent control measure.

Much work has been done in the steppes of the former USSR on the effect on crop production of planting shelter belts of trees (Albenskii and Nikitin, 1956). Shelter-belts were extensively planted in the semi-arid plains of the USA in the late 1930's, for providing protection against wind erosion (Johnson et al., 1983).

Whilst some conflicting results have been reported, the vast majority of studies report beneficial effects due to windbreaks, and their value in the semi-arid regions of the world is well documented (Rosenberg, 1967).

The principal effect of windbreaks is to reduce wind velocity and turbulence. This in turn affects air and soil temperature, humidity, evaporation, snow retention, soil moisture, radiation interception by the crop, and effects of the roots of the shelter trees, shrubs or other plants on the crop (Cannell and Weeks, 1979).

Properly oriented barriers reduce wind erosion forces by more than 50% from the barrier leeward to 20 times its height (Skidmore and Hagan, 1977).

Windbreaks have been very successful in areas where an appreciable part of the total precipitation is in the form of snow, as they aid in uniform distribution of the snow, and thus improve the supply of moisture to spring-grown crops (McGinnies et al., 1963). While all reasons for the beneficial effects of windbreaks are not known, the favourable distribution of soil moisture, and the favourable influence on the internal water régime of sheltered plants, are considered by Rosenberg (1967) as probably the most important. In semi-arid windswept regions where irrigation is

practised, the frequent dry winds with relatively high velocities and high temperatures increase the horizontal advection of energy. Under these conditions windbreaks are effective in reducing evapotranspiration and decreasing plant water stress. By preventing turgor loss and stomatal closure, photosynthetic potential is increased.

As a result of these effects, windbreaks increase the efficiency of water use not only in semi-arid regions, but also in deserts where oasis-type irrigation is practised.

In the former USSR it was found that the yields of grain crops were increased by 20–30%, and those of some grasses by 100–200%, in the sheltered zone. The advantages of the shelter belts were most marked in years of drought, as utilization of the limited water available for transpiration was more efficient by the sheltered crops than by others (Albenskii and Nikitin, 1956).

Drawbacks. Windbreaks take considerable land out of crop production, because of the space they require, and the competition with crops for light, water, and nutrients for a significant distance from the trees.

They also obstruct irrigation systems, are damaged by drift of herbicides, and harbour insects and disease organisms. Farmers also object to the inconvenience of having the land divided into relatively narrow strips, which make it more difficult to operate the increasingly wide modern tillage equipment near the barriers, leaving a haven for seed-propagating weeds.

For these reasons, many shelter belts were removed in the USA in the 1960's. Some shelter belts also died during periods of prolonged droughts (Johnson et al., 1983).

Kinds. Experience has shown that windbreak efficiency is increased by increasing permeability. A dense windbreak causes air to descend abruptly behind it, producing turbulent eddying. If about 50% of the wind passes through the barrier, this air flow will prevent the air from descending abruptly to the ground (Fournier d'Albe, 1958) (Fig. 9.4). A permeable windbreak reduces the wind speed less, but the effect persists for a greater distance downwind. The shelter belts planted during the dust-bowl years in the Great Plains were of the dense type and were for this reason of low effectiveness (Rosenberg, 1967).

In recent years, single-row shelter belts are preferred over the traditional multi-row shelter belts, with wider and more permeable spacings between the trees (Frank and George, 1975). Tap-rooted trees are chosen, that compete less with the neighbouring crops.

In subtropical semi-arid Africa, trees such as *Acacia albida* are used, which serve not only as windbreaks; the leaves and pods provide important sources of fodder for livestock during the dry season and the trees also improve soil fertility (Dancette and Poulain, 1968). Other multi-purpose windbreaks, mentioned by Ben Salem and Palmberg (1985) include *Azadirachta indica* and *Parkinsonia aculeata* in Yemen; *Eucalyptus microtheca* and *Acacia mellifera* for black cotton soils in the Sudan; *Prosopis cineraria* in India and Pakistan; *Leucana leucocephala* in Latin America.

Besides trees, tall plants, such as bamboos, castor beans, elephant grass, etc., planted in rows at regular intervals in fields of low-growing crops, can make quite

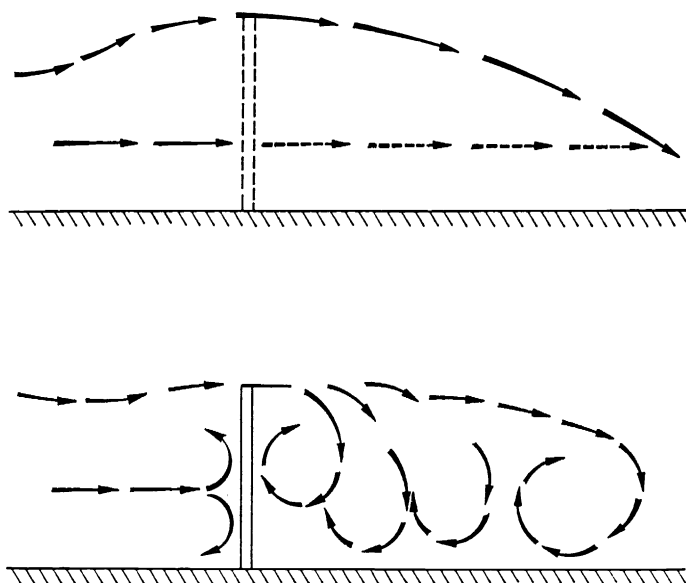


Fig. 9.4. Effectiveness of a windbreak in relation to its permeability.

effective windbreaks. A number of studies have shown that crops sheltered by annual wind barriers grow taller, produce more dry matter, have larger leaf area indices and higher yields. Sheltered soybeans, for example, yielded as much as 25% more than those grown in open field (Radke and Hagstrom, 1976).

Destruction of soil cover

Overgrazing

In humid regions, both tropical and temperate, pastures not only conserve soil fertility but may even improve it. Nutrients and humus accumulate under the sward, conditions are favourable for biological activity, a good soil structure is preserved and the vegetative cover prevents erosion.

In the drier zones, the ecological balance is extremely fragile and is easily upset by overgrazing, which in most of the drier parts of the subtropical and tropical regions has seriously damaged the carrying capacity of rangeland.

The main sources of forage supply to domestic animals in the world, and in particular in the developing countries, are the natural pastures or rangeland, which account for nearly one-quarter of the world's land area (FAO, 1978).

Overgrazing by all types of livestock harm the range. Apart from the excessive

defoliation, too high stocking densities cause soil compaction, thereby increasing run-off and soil erosion. Sheep further exacerbate the damage by grazing very close to the ground, making it difficult for the herbage to recover.

A much maligned animal is the goat. Overgrazing by goats was generally considered to be the major factor in the erosion of soils in the Mediterranean region, because they are frequently the dominant type of livestock found on overgrazed lands. However, the overgrazing was due to excessive numbers of cattle, sheep and goats; the latter are the only ones to remain because only goats are able to subsist on the remaining shrubs and unpalatable herbs.

The direct effect of overgrazing on the ground cover is compounded by certain other practices, such as the cutting for fuel of surviving trees and bushes, uncontrolled burning of dead grass and the use of animal manure as fuel.

The reclamation of grazing land by re-seeding with suitable species including grasses, legumes and shrubs, and proper grazing management is possible but costly and difficult to implement in areas of nomadism. The production of forage reserves, in particular under irrigation on relatively limited areas, or integrated grazing-arable systems can also provide viable solutions.

Improving the grazing lands in neighbouring regions with better precipitation can also relieve grazing pressure in the more marginal areas.

A solution adopted in Senegal as a means of reducing the risks of overgrazing is to restrict stock raising by pastoralists in the dry areas to the production of young animals. At the time of weaning these are sent to the cultivated areas, where they are fed on grown forage and crop residues, and used as a source of traction, manure, milk and meat. Upon reaching maturity or after being retired from work, the animals are fattened and sold.

Burning and its effects

Burning of bush and grass in savannahs and steppes either occurs spontaneously by lightning or periodically by man, for agricultural purposes or to facilitate hunting. Fire has always been the most simple and easy way to get rid of excess vegetation. The cultivator uses fire to clear the land for crop production and to provide plant nutrients. For the pastoralist fire is a means of removing impalatable vegetation, preventing brush encroachment over the pasture and reducing parasites and the vectors of disease.

Burning can be damaging: it destroys the surface cover of vegetation and of organic matter, baring the soil surface to the effects of rain, wind, trampling by stock and game and thereby reducing its resistance to erosion and breakdown in structure. Some useful trees are damaged and a gradual build-up of fire-tolerant, low-productive species occurs (Lagemann, 1977).

Burning has been a major factor in the change from forest to savannah.

Burning in shifting cultivation has not been harmful as long as the fallow period has been sufficiently long to allow the original forest vegetation to recover. With a

shortening of the fallow beyond a critical limit, fire has been a contributing factor to the changeover from forest to brush and from brush to grasses.

In brief, when properly managed, the advantages derived from burning may outweigh its drawbacks. Otherwise it may be a major contributor to the degradation of vegetation and to erosion.

The sudden removal by fire of the protective cover of vegetation in general and of forests in particular may have considerable effects on the watersheds by increasing erosion and water run-off.

After a wild fire destroyed the chaparral scrub in the Arizona foothills, run-off increased from 4 to 40% of a seasonal rainfall of 600 mm, and soil losses increased 1000 to 3000% (Glendening et al., 1961).

Whilst overland run-off and stream flow increase markedly, infiltration is reduced and becomes insufficient to recharge the aquifer. As a result, the flow from springs is reduced or ceases entirely, and the water level of the aquifer is lowered. Shallow wells may dry up completely (Pereira, 1973).

Desertification

Extent of the problem

Le Houérou (1976) defines desertification as a “combination of factors leading to a more or less irreversible reduction of the plant cover resulting in the conversion into desert landscapes of tracts that did not formerly have desert characteristics”.

The climatic and man-made factors that lead to desertification include low and erratic rainfall, high evaporation losses resulting in low effective moisture content, high run-off losses caused by surface sealing and low infiltration rate, low vegetative cover and denudation, and strong and turbulent winds. Debatable issues are whether the spread of desertification is due to transient climatic change, long-term climatic change or man-induced climatic change (Lal, 1979).

In the Sahel, several consecutive years (1968–1973) with below-average rainfall, that also extended eastward towards Ethiopia and Somalia, resulted in Lake Chad shrinking to one third of its normal size, reduced the flow of the Niger and Senegal rivers to an extent that deprived much of the irrigated areas of Niger, Mali, Senegal, Mauritania and Burkina Faso of their water. Death of shrubs and trees and overgrazing by famished livestock, stripped the land of its vegetative cover and left a scorched earth. An estimated 100 000 to 250 000 people died, nomadic pastoralists lost from 50 to 90% of their livestock, and a mass migration to the towns occurred with resultant socio-economic disruptions (Tolba, 1979). The author concludes that “Similar catastrophic droughts have occurred in the past, and will recur in the future. They are an inherent feature of rainfall in semi-arid and sub-humid territories and a principal cause of the fragility of their terrestrial ecosystems”.

Desertification occurs on the fringes of all the hot deserts in the world, on all

continents, generally where rainfall is between 100 and 200 mm, occasionally in even somewhat more humid situations.

The risk of desertification is a function of both the inherent vulnerability of the region and of human or animal pressures on its resources.

As much as 95% of the total land area in the arid and semi-arid zones is exposed to the risk of desertification, with most of the arid zone classified as high risk. However, desertification is not confined to dry areas, and the hazards can be great even in the subhumid zones.

Desert encroachment is expanding at an alarming rate in the Sahelian belt of Africa, from the Sudan to Niger.

The process of desertification has been reconstructed by Bryson (1972) in his studies on the Rajputana Desert, an area once occupied by a high culture with an agricultural base – the Indian civilization. The remains of this civilization as well as palaeobotanical studies indicate that the region was not always as desertic as it is now, but probably a kind of savannah. Bryson describes the history of the area and the probable course of events that led to desertification as follows.

Nocturnal temperatures, with clear skies and over vegetation-covered areas, are lower than they are over compact, bare desert soil covered by a pall of dust. With the high dew point of the Rajputana Desert, heavy dew would form on the vegetation, helping the plant cover to grow and hold down the soil. As a result there would be less dust in the air, less subsidence and more frequent showers. Hence, the vegetative cover maintained a favourable climate, which in turn stimulated plant growth. As a result of overgrazing, the vegetative cover was destroyed and the earth which was no longer protected was exposed to wind erosion. Because of the effect of a high dust content of the air on radiative cooling, the air over the desert subsides more than it would do otherwise, and as a result there are less showers. In brief, the desertification process described is basically a man-made phenomenon.

The expansion of desertification on the fringes of semi-arid areas is the direct result of excessive population pressure and the concomitant rise in the numbers of livestock. As primitive animal husbandry is the dominant land use of the drier areas, overgrazing is the primary factor in desertification.

Box (1981) notes that centuries of Chinese history show alternate periods of reasonable economic pastoral use of the steppes and deserts interspersed with periods when excessive demands were placed on the arid resources by faraway governments in the humid east. Numerous buried cities bear testimony to the former existence of productive grasslands. The most recent episode in these cycles was when the government of the People's Republic of China, during the 'Cultural Revolution', imposed increased production quota on the pastoralists without regard to the ecologically sound carrying capacity of the rangelands. This policy has led to widespread desertification of steppes and desert fringes of China.

Otterman (1974) observed the higher albedo of the heavily grazed areas on the Egyptian side of the border in northern Sinai, as compared to the Israeli side, with an

adequate plant cover due to less grazing pressure; he reasoned that greater reflectivity of the soil surface, due to destruction of vegetation, would reduce surface temperatures, lower sensible heat flux to the atmosphere, and suppress convective shower formation. Sud and Fenessy (1982), in modelling the influence of surface albedo in semi-arid regions, tend to confirm Otterman's hypothesis.

Grove (1985) sums up the foregoing by stating: "... heavy grazing, cultivation and collecting wood fuel may cause climatic as well as biotic deterioration; an expanding desert thus feeds on itself".

In northern Uganda, at the top of the headwater catchments of the Nile, the savannah country receives an annual rainfall of 500 to 750 mm, adequate to maintain an open woodland of well-developed trees with a rich flora of grasses. This productive grassland has been reduced to thornscrub with desert grasses as a result of persistent overgrazing. Run-off from the bare and compacted soil is so great that roads and bridges are persistently damaged by torrent flows, whilst water in the boreholes becomes increasingly scarce. Efforts to mitigate the situation by creating additional watering points through building earth dams and drilling boreholes resulted in a rapid increase in the cattle population around the new water sources and an extension of the area of destruction (Pereira, 1973).

Overpopulation in the dry regions leads to overstocking in areas that are inherently fragile ecosystems. Combined with a lack of range management, the result is the destruction of plant cover, large-scale erosion and finally – in many cases – desertification. The process may be accelerated by the incidence of a series of more than usually dry years, such as recur periodically in the dry regions.

Desertification can be halted only by adjusting stock numbers to the carrying capacity of the land. This is basically a political and social problem, requiring a policy of land management and its effective implementation. The framing of the policy is dependent on a knowledge of the potential productivity of the land. Certain technical measures can be taken to improve carrying capacity, such as the planting of drought-tolerant shrubs and trees, the creation of forage reserves from seasonal surplus vegetation or from small irrigated areas, control of bush fires, improved grazing management, etc. However, in the medium- and long-term perspective, these measures will probably be ineffective if the population explosion is not brought under control (Le Houérou, 1976).

Dregne (1988), in summarizing the debates of a UN conference on desertification writes: "As the consultations progressed, it became apparent that human misuse of the land was at least as important a contributing factor as drought. Poverty, ignorance, or greed are the indirect causes of desertification. The direct cause is mismanagement of the land through practices such as overgrazing, tree cutting, improper tillage methods, poor water distribution systems, and overexploitation. This means that desertification control is a matter of natural resource management, with emphasis on cropland and rangelands". It should be added that for the author "desertification is simply another word for land degradation, but in an arid land context".

Population pressure and shifting cultivation

In parts of the tropical and subtropical regions in Africa and Latin America, high population densities have caused impoverishment of the land. In these regions, shifting cultivation is the most widespread system of land utilization. It has proven to be a relatively safe method for conserving soil, vegetation and fauna, whilst providing subsistence to the population, as long as the population density remained below a critical figure.

According to De Wilde and McLoughlin (1967), an average population of 20 per km² may be compatible with maintaining yield levels on typical plinthite soils by using the traditional bush-fallow in the forest zone. On fertile soils and with an ample and well-distributed rainfall, the critical density may be around 40 to 50 per km². On the other hand, where rainfall is scant and soils are poor, the critical density will be around 10 to 15 per km².

With the reduction of the fallow period, fertility also declines, gradually at first, but the process soon becomes a vicious spiral. As yields fall, more land must be cultivated, the fallow period is further reduced and the rate of degeneration increases, so that the soil is no longer capable of producing even the low yields considered as a bare minimum. The system of shifting cultivation therefore becomes self-destroying once the 'critical population density' has been exceeded.

When this stage is reached, farmers are forced to change from shifting to sedentary farming, first on a portion of the land nearest to their homes and then in gradually expanding circles.

The transition from sedentary farming can only be self-sustaining if measures are adopted to replace the nutrient-restoring and soil-protection effects provided by the plant cover in traditional shifting cultivation.

On steeper slopes, however, the process of soil deterioration and erosion caused by the breakdown of shifting cultivation as a result of population pressure is practically irreversible, as evidenced by thousands of square kilometers of denuded mountainsides bare of soil, visible when overflying these devastated areas.

Salinization and alkalization

Irrigation projects constitute new agro-ecological systems, with resultant radical changes in the environment. Irrigating the soil is *not* the equivalent of creating a humid climate environment; irrigation has specific, far-reaching effects on soil fertility, which have no counterpart in the conditions encountered in humid climates.

Because natural dryland systems are inherently unstable, they "have a limited capacity for assimilating, withstanding and responding to inputs of water, chemicals, and energy that are associated with an irrigated agro-ecosystem. Problems of salinization and other forms of fertility deterioration are in fact symptoms of manipulation exceeding the natural capacity of the ecosystem" (Kassas, 1977).

Irrigation water contains considerable amounts of salt in solution. Even a high-

quality water, with a chlorine content of 200 mg/l, which is considered a low, safe level, can add annually, under normal irrigation practice, up to 3000 kg/ha of NaCl; this does not even take into account the other salts that are present and inevitably get added to the soil.

It will be easily recognized that constant additions of salts of this magnitude can cause considerable changes in the soil's characteristics and fertility. The mechanism of these changes, the nature of the damage caused, the need for special precautions to be taken, and the special methods that can be applied to avoid permanent damage to irrigated soils resulting from salinization and alkalization, as well as the attendant waterlogging, are discussed in detail in Ch. 13.

The problems posed by irrigation agriculture are not new. Early civilizations in the Indus Plains, in the Tigris–Euphrates valley (cf. p. 384), in the Peruvian coastal region, and elsewhere, collapsed as the build-up of salts and rising water tables led to a gradual decline in yields and finally to crop failure (Aronson, 1985).

In view of the adverse effects of irrigation, and the lack of appropriate technology to overcome the problems, there is small wonder that many early civilizations based on irrigation agriculture ended in disaster.

The problems are no less severe in modern times. Salinity is still the most important problem of irrigated agriculture (Dregne, 1976) and it is estimated that approximately one-fifth of the irrigated lands in the world is salt-affected (Maas and Hoffman, 1977).

In the Mediterranean region alone, some 15 million ha of irrigated land have become salt-affected (Le Houérou, 1984). In India, over six million ha have been rendered useless by salinity and waterlogging. In the Punjab, in a single year (1942–1943) more than 280 thousand ha were lost to agriculture for these reasons (Bharadwaj, 1961) (Fig. 9.5).

Nor is damage from irrigation limited to primitive agricultural methods. Describing agriculture in the North American semi-arid plains, Bowden (1979) writes that “despite mechanical gadgetry and scientific analysis used by the farmer and the various government agencies helping him ... irrigation is poorly managed and, when available, water is applied in excessive amounts. The result is rapid depletion of water and leaching of the fertile A-horizon of the once rich prairie soil”. In the USA as a whole, annual losses of cropland due to salt build-up are estimated to amount to 80–120 thousand ha (Yensen et al., 1981). White (1973) sums up the situation by stating that as efforts are made to bring more land under irrigation by harnessing rivers and building canals, a roughly equivalent area is being lost as a result of salinization.

The ‘irrigation district’ of the Imperial Valley in California can serve as an example of the progressive deterioration of irrigated lands and of successful efforts to overcome the problem. In this region an area of 200 000 ha was irrigated with an annual quantity of water of approximately 3600 million m³. The irrigation water contained approximately one metric tonne of salts per 1000 m³ of water. Irrigation was started

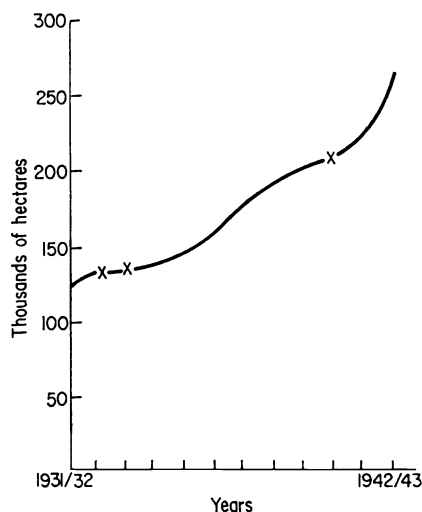


Fig. 9.5. Areas damaged by salt accumulation and waterlogging in pre-partition Punjab. From Bharadwaj (1961). © UNESCO 1961. Reproduced by permission of UNESCO.

in the valley in 1901, and by 1919, 25% of the irrigated land had already been affected by salt accumulation and a high water table (Thomas, 1956). Drainage was initiated subsequently, but was not sufficiently extensive to prevent continued damage in most of the area. By 1940, the water table was at less than two metres depth, and salt was accumulating at a rate of two-and-a-half tonnes per hectare per year! By 1950, methods for adequate drainage had been developed, and, in the course of less than a decade, the entire area had been successfully reclaimed.

Deterioration and loss of water resources

Increasing amounts of water are being made unsafe for human consumption, livestock, recreation and irrigation by organic and mineral pollutants. These include excess plant nutrients and residual agrochemicals (cf. p. 427), animal wastes, municipal and industrial wastes, etc. (Levine et al., 1979). Industrial wastes have severe local effects, but their impact is still limited in most developing countries; for them, chemical pollution is more of a potential danger than actual.

The detrimental effects of acidic precipitation on fish and other parts of the aquatic ecosystem are a potential danger in the developing countries. This pollutant can be transmitted over very long distances. With increasing industrialization and the concomitant neglect of expensive control measures, acidic precipitation may increase the degradation of water quality.

Large-scale surface water storage

River basin development projects are of major importance for economic programmes and sources of water for irrigation and of electric power for industrialization. However, many environmental problems may arise as a result of the implementation of these projects, such as the spread of water-borne diseases, the drying up of downstream fisheries, the inundation of valuable agricultural and forest land and the displacement of population. Some of these adverse effects emerge gradually; others are more rapidly evident. Some, after they have occurred, are practically irreversible. Therefore, planning must take into account the possible negative effects of these schemes, and attempt to avoid or mitigate them. Evidence is increasing that many of the spectacular works undertaken in developing regions to store river water on a large scale were ill-conceived. They are also always expensive and extremely wasteful of water.

As dams grow higher and reservoirs larger the problems multiply. The spread of water-borne diseases accelerates, water losses through evaporation increase and salinization and sedimentation become more serious. Greater populations are displaced, with all the attendant social and economic problems (Borgstrom, 1973).

Losses of water by evaporation

Evaporation is very high in the arid regions which are to be served and in which the reservoirs are frequently located, and can amount to as much as 125 cm annually (Stamp, 1961). As much as three-quarters of the water stored may be lost by evaporation (Dixey, 1966), and the remaining water becomes increasingly saline. As a result of the extremely high rate of evaporation, the total yield of a watershed in an arid region is actually decreased when large reservoirs are built. There is even a point at which the building of additional reservoirs causes a net deficit in usable water, when aggregate evaporation losses exceed the amounts of usable water gained (Burgy et al., 1967).

No techniques have yet been developed for reducing evaporation losses from very large reservoirs. For the enlarged Aswan reservoir, the loss by evaporation has been estimated as equivalent to 10% of the annual flow of the Nile (Addison, 1961).

Impairment of water quality

The salinity of the water flowing into the reservoir may vary considerably in the arid regions, depending on rainfall distribution, the salinity of the watershed and the changing rates of evaporation.

All water evaporating from reservoirs and lakes must leave a residue of salts which increases the salt content of the stored waters. When the rate of evaporation exceeds the rate of water inflow, the situation may deteriorate at a fairly fast rate, the loss of water being compounded by its increasing salinity.

The salt content of the water in the reservoir will be at its lowest after the main

flood flow during the rainy season and will reach its highest concentration towards the end of the dry season. The higher the surface–volume ratio, the greater the rate of evaporation and, as a result, the higher the salt concentrations.

Useful life span of reservoirs

‘Reservoirs are mortal’ (Addison, 1961) and once filled up with sediment the site is irretrievably lost for further use as a reservoir. The life span of reservoirs has frequently proven to be far shorter than planned, especially when the necessary measures to protect the catchment area are not taken or are inadequate.

Semi-arid lands have higher sediment yields per unit area than any other environments; reservoirs also need very large catchment areas in order to be supplied with large quantities of water. The cumulative effects on the reservoirs are: (a) addition of enormous loads of sediments annually; (b) the storage capacity is rapidly reduced; (c) an increase in the surface–volume ratio; and (d) a relative increase in losses by evaporation (Grove, 1985).

The cutting of trees and destruction of natural vegetation on mountain slopes increases the rate of erosion and results in the siltation of rivers, reservoirs and irrigation canals.

The incidence of floods in India and Pakistan has increased considerably in recent years because of the rise of river beds due to silting with soil washed down from the denuded slopes of the watersheds.

The life expectancy of the 600 million dollar Mangla reservoir in Pakistan, originally estimated as 100 years, has been reduced by half because of an increase of the rate of sedimentation resulting from clearing the steep slopes of the watershed for farming and from overgrazing (Brown, 1977).

The Ksob dam in Algeria became first partially then completely unusable within the space of ten years, well before the additional harvests had been able to pay off the very high construction costs (Dumont, 1966).

Experience in South Africa has shown that reservoirs have filled up with sediment within a dozen years. In the Levant and in Sinai, relatively small reservoirs have filled up in a still shorter period. It is true that certain reservoirs have a longer life expectancy: in the USA, the great reservoirs are expected to remain effective for one or two centuries. However, even in the USA there are examples of reservoirs that have silted up completely within a few years. New Lake Austin on the Colorado River in Texas lost 95.6% of its capacity in 13 years and the Grand Reservoir on Toulumeme River in California lost 83% in 36 years (Kassas, 1972).

Invasion by water weeds

Invasion of water reservoirs by water weeds may also severely impair their effectiveness.

The water hyacinth (*Eichhornia crassipes*), originally introduced into Africa for its

decorative value, has become a serious pest of waterways and reservoirs because of its remarkable powers of spreading. Thousands of miles of the Congo River are infested; it is also now well established on the Nile. Enormous expenditure has as yet failed to give satisfactory control (Ivens, 1967).

Another weed that invades reservoirs in Africa is *Salvinia auriculata*, a free-floating, branched fern, introduced from South America. Under favourable conditions the plants can cover large areas with a thick layer of vegetation. First observed in East Africa in 1957, it now covers hundreds of square miles with a mat up to 25 cm thick – in particular in Lake Kariba, the Kitali dam in Kenya and in Lake Victoria (Ivens, 1967).

The major effects of weed invasion of reservoirs have been summarized by Little (1969): they form large mats which may block hydroelectric installations, feeder streams and irrigation outlets; they make fishing more difficult and by inducing deoxygenation increase fish mortality; they reduce the effective capacity of the reservoirs; they provide excellent breeding grounds for many disease-transmitting vectors. The association of aquatic weeds with the spread of certain vectors of disease in man and animals is one of their major negative effects. *Bulinus* and *Biomphalaria* snails, which are intermediate hosts for schistosomiasis, flourish under the protection of aquatic weeds. The development of vegetation like *Pistia* and *Polygonum* favours the genus *Mansonia*; weed-infested waters provide a suitable breeding place for culex (White, 1977). Polunin (1972) adds that there is a possible loss of photosynthetic activity of phytoplankton and benthic algae at lower levels, due to interference with the light supply and a concomitant loss of biological productivity in the body of water.

Environmental effects

After high-level dam construction, infiltration of subsoil water streams may extend for ten or even hundreds of kilometres both up- and down-stream of man-made lakes, causing a rise in the level of groundwater. If the rise is stabilized beyond a critical level of 1.5 to 2 m, alkalinization and salinization may result. Extensive erosion and landsliding may also occur along the banks of reservoirs, causing the loss of agricultural land (Kovda, 1977).

Rivers normally carry considerable amounts of sediments, of which part is deposited on the irrigated land, contributing to its fertility, and part is deposited in the deltas and counteracts wave erosion from the sea. After construction of the Aswan Dam, the reduced sediment rate no longer fulfils these roles effectively and the coastline is suffering heavy damage.

Fishing in the formerly highly productive estuaries and coastal waters is seriously affected, and – in the case of the Nile – has dropped from 18 000 t in 1965 to 500 t in 1968 (Dorst, 1972).

*Excessive exploitation of groundwater resources**Land subsidence*

Excessive pumping may lead to a subsidence of the land surface, resulting in compaction and the reduction of pore space in the aquifer. The loss of underground pore space is a permanent reduction of the underground storage capacity and is therefore an irreplaceable loss.

Peat lands under irrigated cropping are particularly subject to subsidence as a result of the oxidation of the peat. The surface of the peat lands in the Sacramento–San Joaquin delta of California has sunk by approximately two metres between 1962 and 1966 (Penman et al., 1967).

Salt-water invasion of aquifers

When a coastal aquifer is open to the sea, seawater forms a wedge underlying the fresh water flowing seaward.

Excessive groundwater withdrawal will cause a lowering of the water table. When the level of the water table becomes lower than that of the saline water, the latter is drawn into the aquifer. This is a frequent occurrence in coastal areas. It is an accepted rule of thumb that decreasing the water level one metre by pumping will lead to a rise in the level of the zone of junction between salt and fresh water of 40 m. Hence, overutilization of the aquifer in coastal regions, which leads to a lowering of the water table, can have a disastrous effect by salinizing the aquifers. Drawing in salt water is even more detrimental than simply depleting an aquifer. An emptied aquifer may eventually be recharged, but in a polluted aquifer withdrawal of water has to cease even when plenty of water is still available. Reclamation is also more costly and difficult.

Pollution by fertilizers

The heavy use of fertilizers in modern agriculture, which has increased fivefold in a quarter century (Harre et al., 1971), and the indisputable fact that only part of the applied plant nutrients can be accounted for in the crops harvested, has inevitably given rise to apprehension as to the possible detrimental effects of fertilizer residues on the environment, in particular on the quality of water resources, with potential hazards to human health.

Potential contribution of fertilizers to pollution

The three main plant nutrients, applied at high rates in intensive agriculture, and therefore potentially dangerous pollutants, are: phosphorus, potassium and nitrogen.

Phosphorus. In most agricultural soils, with the exception of sands and peats, the phosphorus applied in water-soluble fertilizers is rapidly converted in the soil into forms with a very low solubility. As a result, phosphate ions have extremely low mobility and it is highly improbable that significant amounts will be leached to the depth of the groundwater. However, it is a fact that many water resources have been polluted with excessive amounts of phosphorus but the main contribution is from the use of detergents with high phosphorus contents, and not the fertilizer used in intensive agriculture.

Potassium. Though most potassium fertilizers are soluble in water, in temperate climates, the potassium applied rapidly becomes immobilized in the soil as a result of adsorption by the soil particles. Though somewhat more mobile than phosphorus, it is extremely unlikely that potassium ions will be leached downwards to appreciable depths in most agricultural soils of the temperate climate. In most tropical soils, potassium is more mobile and is subject to leaching.

Nitrogen. Under normal soil conditions favourable to crop production, the nitrogen applied in fertilizers, whether in the form of ammonium, ammonia, urea or other organic compounds is rapidly nitrified into highly soluble nitrates, which are not fixed by the soil particles and can move rapidly through the soil.

Therefore, a priori, nitrogenous fertilizers would appear to be the most likely potential source of contamination, especially as the amount of fertilizer nitrogen used in the world has increased at a phenomenal rate – far more than that of the other plant nutrients.

Gilliam et al. (1985) state that complete recovery of N in plant and soil is seldom attained and the fate of the unrecovered portion cannot be determined, which they call 'the nitrogen enigma'. The recovery of fertilizer N is seldom over 50%, and often as low as 20% (ibid.).

Deleterious effects of N pollution

Human health. Excess nitrogen has a number of deleterious effects. A direct relationship has been established between the levels of nitrates in water and human health; hence, legislation in most countries defines the maximum allowable nitrate content of drinking water. However, it is not the possible toxicity of NO_3 that is the only cause for concern; the nitrate content is simply a useful indicator of: (a) the amounts of toxic nitrites that may be introduced in the blood stream through the reduction of nitrates after ingestion; and (b) the degree of faecal contamination of the water leading to enteric infection. The latter is by far the more important consideration and has no relation whatsoever to fertilizer application.

Eutrophication. Eutrophication is a process in which the levels of nutrient salts in

water are increased. The levels of nutrients and their proportions in relation to each other largely determine the type of vegetation found in rivers and lakes.

A steep increase in plant nutrients in the water may cause a proliferation of certain algae, upsetting the biological balance of inland waters such as lakes and reservoirs. The rapid multiplication of these algae may prevent or considerably reduce the penetration of sunlight to the subsurface water, preventing the photosynthetic process in algae which normally develop in these lower layers. As a result, the production of oxygen is reduced and anaerobic conditions are created. The organic remains of the increased mass of organic matter produced by the proliferating algae of the surface waters, which sink towards the bottom, are decomposed by bacteria and further exacerbate the anaerobic conditions. Undesirable changes occur in the colour, taste and odour of the water, making it unfit for drinking purposes.

The main nutrients involved in eutrophication are nitrogen and phosphorus. Both have to be present at a certain level for the process described above to occur (Mellanby, 1972). Whilst most of the phosphorus that contributes to eutrophication comes from detergents, the role of fertilizers in supplying the nitrogen involved is more controversial (see below).

Actual contribution of fertilizers to pollution. It is extremely difficult to prove or disprove a direct relation between the large amounts of fertilizer nitrogen used in intensive agriculture and the increased pollution of many water resources, whether groundwater, streams or lakes.

It is usually not possible to determine the amount of nitrate that is leached from the soil; in addition, fertilizers applied are not the only possible source of the leached nitrate. The decomposition of organic matter in the soil and the fixation of atmospheric nitrogen by bacteria or algae are processes that are highly beneficial to agriculture and which are enhanced by good crop management practices. These can contribute amounts of residual nitrates far greater than those derived from the fertilizers applied.

It is also almost impossible to identify the source of nitrates found in water. Sediments due to soil erosion and sewage effluent, whether treated or raw, the wastes from modern feedlots on which large numbers of livestock are concentrated, food-processing wastes, industrial effluents, are all sources of contamination that have increased concurrently with the augmented use of fertilizers in agriculture.

The few studies that have been made on changes of nitrate content of groundwater and of river waters draining out of well-farmed land in the course of 10–20 years have given conflicting or inconclusive results.

Broadbent and Rauschkalb (1977) in a study in the San Joaquin Valley in California, found that at the levels of N application that gave the highest yields of maize, the amount of residual nitrogen in the soil was relatively small; it was only at levels higher than those needed for maximum yields, that the amounts of leachable N increased steeply (Fig. 9.6).

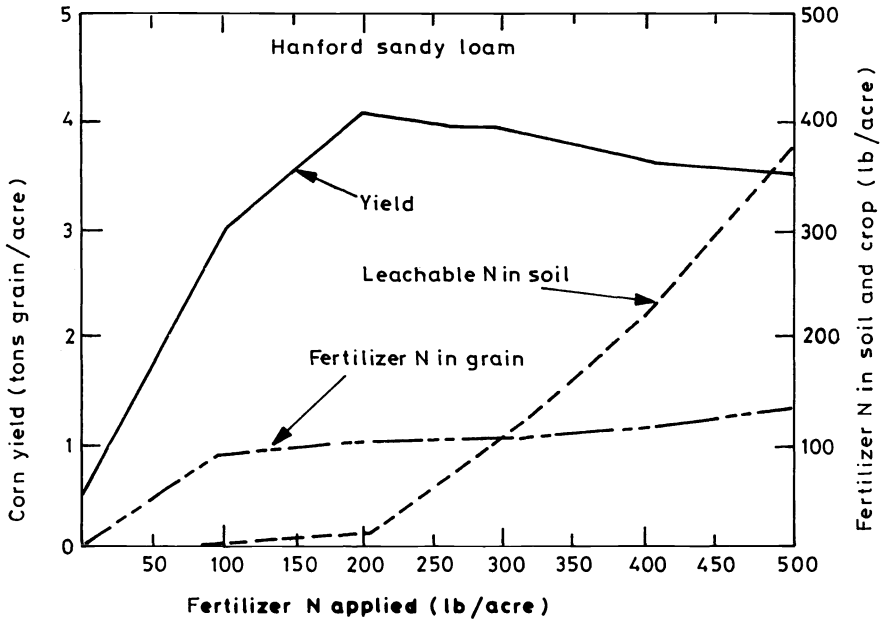


Fig. 9.6. Nitrogen fertilizer application and potential water pollution. From Broadbent and Rauschkalb (1977). By permission of the American Society of Agronomy.

During the period 1934–1963, during which fertilizer use on the irrigated valley land adjacent to the Upper Rio Grande of New Mexico increased manifold, a substantial decline in the nitrate content of the river water actually occurred (Bower and Wilcox, 1969).

On the other hand, groundwater investigations in California showed that in at least two areas, the principal sources of nitrogen pollution of groundwater were directly related to the increased use of nitrogen fertilizers in irrigation agriculture (Ward, 1970). Bingham et al. (1971), in a study in a citrus watershed in California, estimated that the loss of nitrogen in the drainage water amounted to 45% of the applied fertilizer nitrogen.

Conversely, it can be argued that an adequate application of fertilizers, by increasing root proliferation and the amount of organic residues remaining in the soil, will improve soil protection by the crop, and therefore reduce erosion, a major contributor to the pollution of streams, lakes and reservoirs.

Conclusions. In brief, there does not yet appear to be sufficient reliable experimental data to state authoritatively whether fertilizers do or do not contribute to the pollution of water resources (FAO, 1972). Common prudence indicates that all conceivable precautions for minimizing pollution of the environment should be taken.

Fortunately, there is no conflict between this requirement and farmers' own direct interests.

Crop management aimed at maximum efficiency in fertilizer use will minimize the amounts of fertilizer residues that might contaminate the environment.

Amongst the management procedures proposed are (Parr, 1972):

- (a) applying fertilizers at rates below those required for maximum yields, namely, at the point of greater economic return;
- (b) proper timing of application to coincide as closely as possible with maximum crop demand;
- (c) alternating deep-rooting crops with crops that have received high rates of nitrogen;
- (d) maintaining cover crops wherever possible;
- (e) use of nitrogen carriers with coated granules enabling a controlled release of nitrogen.

In any case, for the developing countries as a whole, the danger of pollution resulting from the use of fertilizers appears, at least for the foreseeable future, to be negligible, because the levels of fertilizer applied are still far below those required for optimum production. For these areas in which the 'green revolution' has resulted in the use of high levels of fertilization, in particular of nitrogen, it is safe to assume that little or no damage will accrue to the human environment if the amounts used are within the limits imposed by economic considerations, and sound management practices are adopted.

Deterioration of natural resources in Third World countries

There are three main reasons for the deterioration of natural resources in Third World countries (FAO, 1989): lack of access to land, inputs and other productive resources by the majority of rural households and communities; lack of awareness among policy makers of the economic costs involved; and lack of environmentally sound alternative technologies acceptable to farmers.

As a result, subsistence farmers have no option but to overexploit natural resources in order to survive. "Everyday security takes precedence over concern to any great extent with the future. Sheer necessity forces them into mining soil nutrients, cultivating steep slopes, overgrazing rangeland, excessive collection of fuel wood, in order to feed and warm themselves" (FAO, 1989).

"In some areas the battle is already lost, in other areas restoring land degradation will be slow, costly and difficult to achieve. Especially in the harsh environment of the semi-arid areas, the cost and level of inputs needed to restore the productivity of degraded lands are much greater, and the benefits to be derived therefrom are much lower than in the temperate humid climates" (Parr et al., 1990).

Sustainable development will require the creation of alternative employment op-

portunities and/or migration to reduce population pressure on the land.

The overall objective of government should be to make it possible for farmers to conserve resources, and no longer be practically forced to destroy them, by circumstances beyond their control.

“In the absence of effective national and international support, the micro-economics of sustainable production systems, household labour availability, and the perceived needs of the rural poor at the local level must therefore be the starting point for national strategy and policy formulation and for guiding those components of the producer support systems that will have to be initiated at the central level” (FAO, 1989).

Sustainable agricultural systems

The problem

Very few farming systems are immune to breakdown as a result of the deterioration of the natural resources on which their survival depends (Parr et al., 1990). This is especially true of many areas in the dry regions which are characterized by a highly fragile natural resource base and are very susceptible to wind and water erosion, as pointed out in a previous section of this chapter.

In some cases, changing circumstances cause the breakdown of the system, as in the case of pastoralism and shifting cultivation, in which increased population pressure beyond a critical limit results in desertification of former rangelands and soil erosion of cultivated areas.

In other cases, the dangers are inherent in the system itself. Arable farming systems in the fringe semi-arid regions are endangered by the extreme variability of precipitation which can result in former prairies and savannahs becoming dust bowls and deserts following cultivation.

Where irrigation is used in order to intensify production and avoid the risks inherent in dryland production, the potential for soil degradation are increased manifold (cf. p. 422).

The one stable agricultural system that has been maintained for generations without impairing productivity (albeit at a very low base yield), is lowland rice production, the exception that confirms the rule.

The capacity of modern agricultural systems to endure indefinitely is not assured. Agricultural systems are no longer oriented to production for the subsistence of the producers, but are capital-intensive economic entities whose sustainability depends first and foremost on economic factors. Economic returns from commercial farming require high levels of inputs, the injudicious use of which can harm the environment and hence, impinge on the rights and quality of life of the public at large.

In recent years public awareness of the dangers inherent in the pollution of the

environment and the concomitant degradation of natural resources has increased to the point that the topic has become a political issue. Though many and diverse economic activities contribute to environmental pollution, much of the attention has focussed on the role and contribution of agriculture. The public at large, and many farmers in particular, are concerned with the dangers of consuming food contaminated with poisonous residues from plant protection chemicals; the pollution of the soil and the aquifer by fertilizers and other chemicals leached from the root zone; the widespread appearance of strains of insects and weeds increasingly resistant to the chemicals used to control them; the disruption of the biological balance in nature, by the indiscriminate killing of wildlife and natural enemies of pests; the degradation of soils by erosion; and the famines caused by widespread desertification. This concern has intensified the search for strategies for addressing the problems that afflict agriculture worldwide, and especially in the dry regions.

The book 'Silent Spring' by Carson (1962), in which the author vividly described the dangers inherent in the widespread use of chemicals in agriculture, also gave considerable impetus to the search for alternative farming systems.

Sustainable agriculture

'Sustainable agriculture' is a loosely defined term that encompasses a number of approaches in the search for alternative systems of agriculture; it implies a time dimension and the capacity of a farming system to endure indefinitely (Lockeretz, 1988).

The ultimate goal of sustainable agriculture is: "to develop farming systems that are productive and profitable, conserve the natural resource base, protect the environment, and enhance health and safety, and to do so over the long term" (Parr et al., 1990).

Two such alternatives that have been proposed are low-input systems and organic farming.

Low-input sustainable agriculture (LISA)

Low-input farming systems "seek to minimize the use of external production inputs, such as purchased fertilizers and pesticides, wherever feasible and practicable; to lower production costs; to avoid pollution of surface and groundwater; to reduce pesticide residues in food; to reduce a farmer's overall risk; and to increase both short- and long-term farm profitability" (Parr et al., 1990).

These objectives are certainly laudable and, if the term 'minimize' would be replaced by 'optimize', could serve as a valid and all-encompassing definition of the objectives of conventional agriculture as practised by experienced and responsible farmers.

Parr et al. (1990) further state that "another reason for the focus on low-input farming systems is that most high-input systems, sooner or later, would probably fail

because they are not economically or environmentally sustainable over the long term”.

From the foregoing, it would appear that the farmer, whether traditional or modern, has only two alternatives: to adopt farming systems based on low inputs, or those requiring high inputs. In reality, there is a third option: *optimal-input farming systems*. These systems, defined by Wagner (1990) as ‘low input per unit of output’ systems, emphasize the law of diminishing returns, which applies to all inputs without exception. A farmer who ignores this basic law, is *not* implementing the established principles of crop, soil, and water management of conventional agriculture, as presented in the professional literature, including this book.

If the farmer does not use inputs at a level that provides optimal returns to his investment, he is harming his own interests because he does not fully utilize the potential of other factors of production. Conversely, if he uses inputs at higher than optimal levels, he not only wastes resources, but risks contributing to environmental pollution.

A shift to the advocated low-input farming is unrealistic for both economic and humanitarian reasons; it would cause a decline in food production and an increase in food prices (FAO, 1989).

Modern agriculture is intrinsically a high-input economic activity in which considerable amounts of capital and know-how are invested. The subsistence farmer who is unable, for economic reasons, to invest in machinery, improved implements and agro-chemicals, implements, must expend an enormous amount of backbreaking work and drudgery, just to eke out a living. The use of all modern inputs at optimal levels (rarely are these *low* levels) is both technologically and economically sound; it is also socially justified. This is the only way that subsistence farming can be transformed into modern, highly productive farming, capable of providing an acceptable standard of living.

A continuation of the low external input agriculture that characterizes Third World countries will only perpetuate the vicious circle of low inputs–low yields from which the subsistence farmer cannot extricate himself by his own efforts. The densely populated agrarian countries of the Third World *must* achieve much higher yields than those currently produced by traditional farming if they are to provide food to a rapidly increasing population. FAO (1989) points out that even China, with its long tradition of efficient biological waste utilization is obliged to supplement organic manures with increasing amounts of chemical fertilizers.

A further point raised by FAO (1989), is that on over 40% of sub-Saharan land it is impossible to produce subsistence needs of an average family of four to five persons, from low external input systems. A Malawan farmer, for example, for whose family maize provides 80% of total calorie intake, needs to produce at least 1500 kg of maize per year. Many farms are already less than 0.5 ha and the average size continues to decline. FAO calculates that such farms must achieve yields of at least 3000 kg/ha grain equivalent now, and twice as much by the year 2010. These yields

are impossible to achieve with low-input systems and barely possible with the best technology currently available.

Present yields from monocropping maize by traditional methods range from 400 to 800 kg/ha; under ideal conditions, these yields could be doubled if sufficient manure was available, and trebled by intercropping and green manures. Such yields would still fall short of those required for survival, and the use of mineral fertilizers at adequate levels (combined with other inputs, such as high-yielding hybrids, improved soil moisture techniques, plant protection) is therefore inevitable.

The situation is essentially similar in most Third World countries in Asia and Latin America.

It is up to the governments of these countries, by appropriate credit, research and extension programmes to make the external inputs available to the farmers and ensure their proper use at optimal levels.

In brief, the slogan 'low-input agriculture' is both misleading and counterproductive. It is misleading because it diverts attention from the really important goal of increasing the farmers' awareness that further deterioration of the natural resource base must be prevented. It is counterproductive, because it provides Third World politicians with an alibi for not providing their subsistence farmers with adequate levels of external inputs required for survival.

Organic farming

The only concept that merits characterization as an alternative agriculture is organic farming, which is not exactly a new approach.

In the 1940's, a school of thought was propagated, inspired by Howard (1940), Balfour (1945), and subsequently many others, that ascribed most of the ills of modern agriculture to the use of 'artificial' chemicals, such as soluble fertilizers, insecticides, fungicides, herbicides and others. They claimed that the chemicals destroyed soil fertility, by replacing organic manures and poisoning the soil organisms; this, in turn, caused an increase in the incidence of plant diseases and thereby adversely affected the health of humans and domestic animals using the contaminated and diseased plants for food.

The amounts of organic food produced still constitute only a very small fraction of total food production and the number of 'organic' farmers in Western Europe and the USA does not exceed 1% of the total number engaged in agriculture in these countries (USDA, 1980). However, their numbers are increasing, mainly as a result of the increase of consumers' interest in environmental problems, improved quality of life and health-giving food.

Principles and methods. "Organic farming is both an agricultural philosophy and a farm management system" (Wolf, 1977), and aims at producing health-giving food of high biological value and long shelf life, without harming the environment. Crops should be grown in their normal environment, in the appropriate season, on suitable

soil and favourable climatic conditions. The soil is to be treated as a living organism and not a chemical laboratory; the major requirement being the maintenance of a favourable soil structure. Crop rotations should be devised that improve soil fertility, are efficient in controlling pests, diseases and weeds, prevent soil erosion, and enable a balanced distribution of labour requirements throughout the year (ibid.).

In contrast with conventional agriculture, organic farming considers that it is not the plant that should be fed, but the soil and its inhabitants. This should be achieved by applying organic matter, which will activate biological activity in the soil and thereby release nutrients for the plants.

Organic farming practice compared to conventional agricultural practice. First, it should be stressed that organic farming, even if it rejects the use of many modern inputs, is not, by any means, a return to the traditional agricultural methods of the previous century, as is frequently insinuated by its denigrators. In levels of sophistication and modernization, there is no difference between organic and conventional agriculture.

The rational use of modern machinery, the adoption of improved varieties of crops – in particular those resistant to diseases and pests – certified high-quality seeds, advanced methods of soil conservation, approved management practices in animal husbandry, proper handling of organic wastes, are principles adopted in both conventional and organic farming.

The major area in which the tenets of organic and conventional farming diverge is in the use of agro-chemicals, such as soluble fertilizers, pesticides, fungicides, herbicides, etc., which is forbidden in organic farming whilst widely used, and often abused, in conventional farming.

Premises of organic farming examined. Organic farming and health. The relationship between organic farming and health, and the professed ill-effects of fertilizers are major areas of conflict between the two systems.

The advocates of organic farming are convinced that their system produces healthier food, of higher nutritive value than conventional farming. This conviction is based on the following assumptions:

- ‘organic’ food is richer in nutrients, and these are in balanced supply;
- it also has a higher content of vitamins and essential micronutrients;
- it is uncontaminated by poisonous residues from pesticides, herbicides, etc.;
- a hitherto unidentified biotic factor is present.

There is no experimental evidence to justify the claim that crops grown on organic amendments alone are healthier and more nutritive than those grown under similar conditions with equivalent amounts of chemical fertilizers. Much of the material of studies of quality effects of organic versus mineral manuring is: “anecdotal in nature, in the form of testimonials rather than controlled studies. And reports of studies

usually neglect statistical analysis and consideration of factors of little interest to the writer, such as the weather, which might have had as much effect as a particular natural technique. ... Unfortunately, for a variety of reasons, valid comparisons of conventional and organic techniques appear to be virtually nonexistent" (Oelhaf, 1978).

It is also extremely difficult to disprove (or prove) statements such as: "the effects on health are said to be manifested not just in one generation, but more importantly, over two or three generations" (Oelhaf, 1978). No less difficult to refute are declarations such as: "Some things chemically the same may be very different as conductors of living energy" (Balfour, 1975) or the existence of an unidentified biotic factor. True believers do not require absolute proofs.

Organic manures versus fertilizers. The major difference between organic and conventional farming, is the almost exclusive reliance of the former on organic matter as a source of supply of nutrients, while the latter will supplement, if necessary, any organic wastes he can obtain at reasonable cost with chemical fertilizers, or will depend exclusively on the latter, if necessary.

There is no proof, nor is there any reason to assume, that nutrients released into the soil solution originating from chemical fertilizers are different in any respect from those supplied by soil organic matter.

Conventional farmers are well aware that the injudicious use of fertilizers can adversely affect the quality of agricultural produce, reduce plant resistance to disease, and potentially pollute the aquifer.

Experience has shown that carefully calibrated and balanced amounts of fertilizers have a large impact on crop yields with negligible environmental damage. If used carefully and in amounts not exceeding the soils' capacity for holding nutrients, pollution by chemical fertilizers can be avoided (Albrecht, 1975). This is confirmed by Newman (1981), who writes: "Although it is popular to blame increased fertilizer use for increased leaching of nitrogen, in practice, inorganic fertilizer in properly timed applications is less likely to produce leaching than is usage of organic manure to produce an equivalent crop".

It is extremely difficult to understand why organic farmers have no qualms about growing crops under irrigation. They fear the ill effects of applying chemical plant nutrients, but blithely add harmful salts contained in their irrigation water in quantities that are many times greater than the amounts of fertilizer applied by the most profligate conventional farmer.

Agro-chemicals for pest, disease, and weed control. The danger of toxic residues as a result of spraying with agro-chemicals is well known. There is, however, no reason to assume that these ill effects cannot be avoided by sensible, responsible farmers. The proper use of these inputs can have considerable beneficial effects. Farmers who knowingly neglect to take the necessary precautions, and do not act in accordance

with the regulations that have been designed to avoid harm to the consumer, are criminals and should be treated as such.

Organic farmers have adopted biological control as if it was exclusively their own answer to pest control. Biological control was developed by main-trend agricultural research and adopted by conventional farmers with considerable success.

However, biological control methods by themselves are seldom fully effective, except in relatively few special cases (Newman, 1981). For this reason, integrated control methods, which coordinate chemical, biological and cultural methods, have been developed and are being increasingly adopted by conventional farmers.

Herbicides. Selective herbicides are one of the most important technological breakthroughs in modern agriculture, making backbreaking manual weeding obsolete. Organic farming rejects the use of weedicides, relying on crop rotation, mechanical means, and, where unavoidable, hand weeding. Organic carrot farmers do however spray with a light oil to control weeds.

Apart from their specific role in weed control, the introduction of short-persistence weedicides, such as paraquat and glyphosate, has made possible conservation tillage which organic farmers also consider desirable.

Economic aspects. Farmers, irrespective of the system they adopt, expect – and are entitled to – a fair return on their investment in capital and labour. Very few valid comparisons between organic and conventional farms have been carried out; differences in the individual professional abilities of the farmers, size of farms, types of crops grown, etc., make comparisons very unreliable.

Very few organic farmers start with a virgin soil; generally these soils have received chemical fertilizers in the past, and the resultant build-up of nutrient reserves in the soil may very well mask any deficiencies resulting from organic farming.

Two conclusions are generally accepted: yields are higher in conventional farming, and organic farming is the more labour intensive of the two systems. Even without quantifying these differences, it is possible to state that in order to compensate for them, the produce of organic farms must be of higher quality, and therefore justify a higher market price than that for produce from conventional farms. It is, however, precisely the matter of differences in the quality of the produce from the two systems which is the most controversial.

As long as organic farmers are a small minority of the farming population, they will always find sufficient believers in the superiority of their produce to justify higher prices.

Conclusions

Conventional agriculture has achieved impressive results in increasing food production and reducing its cost to the consumer. One cannot however ignore the harmful

effects on the environment and on human health that have resulted from the excessive and careless use of modern inputs.

There is a general consensus that these dangers must be recognized and avoided. In attempting to achieve this objective, conventional agriculture has developed many new technologies that minimize or cancel the negative effects on the environment of certain agro-chemical inputs. Organic farmers should be congratulated for adopting and propagandizing the precepts of sound, sustainable farming. These were developed by main-stream research for the benefit of *all* farmers, irrespective of the system they prefer to adopt. The pretension of organic farmers that they alone use technologies that are environment-friendly and beneficial to human health, whilst it is in the nature of conventional farmers to be irresponsible in this respect, is unjustifiable.

The major difference between the two concepts of farming is that the sensible conventional farmer adopts those practices that he considers as economically justified *and* not harmful to the environment, whilst the organic farmer acts on the basis of a deep belief in, and commitment to, certain basic concepts, even if they have not been validated scientifically, and even if farming in accordance with these beliefs is not the most profitable. The insistence of organic farmers that the use of many modern inputs, mainly agro-chemicals, should be proscribed, is a self-imposed limitation lacking empirical or scientific validation.

Whilst many conventional farmers are becoming far more circumspect in their use of modern technology, there are also indications that some organic farmers are becoming less strict in forbidding agro-chemicals. In Western Europe and in the USA, organic farmers are beginning to use moderate amounts of fertilizers, in order to supplement organic manures, and to include herbicides in an integrated approach to weed control. The energy crisis, and the resulting steep increase in the cost of agro-chemicals, has forced *all* farmers to reappraise their management procedures. The major changes that have been recommended and frequently adopted in the wake of the energy crisis have been (Arnon, 1987): to replace monoculture, wherever possible, by appropriate cropping systems; to supplement chemical fertilizers by organic manures, when available; to aim at optimizing production instead of maximizing yields, thereby reducing fertilizer and water inputs considerably; to use integrated control of insects, diseases and weeds instead of exclusive reliance on chemicals; to adopt a conservation tillage system instead of clean tillage and to choose varieties that are widely-adapted, have high yield potential, and are resistant as much as possible to diseases, pests and environmental stress.

By foregoing the marginal increase in yields due to the last increments of fertilizers and water, considerable savings in energy requirements can be achieved with relatively small sacrifices in yield. Therefore, the need to reduce pollution dangers, to limit energy-consuming inputs as well as purely economic considerations coincide in determining optimum levels of use of off-farm inputs.

These goals "can be achieved by the application of established principles of soil and water management to crop and livestock production" (Parr et al., 1990).

Recapitulation

In brief, the search for an alternative agriculture [a euphemism for organic farming recently adopted by some authors (National Research Council, 1989)] is superfluous. What is needed is an economically *and* environmentally efficient agriculture based on principles and practice that “have been a century in the making” (Wagner, 1990).

Farmers should be sensible and responsible; they should realize that safeguarding the environment and providing abundant and healthy foods to the population are not in conflict with their own short-term as well as long-term interests.

These conventional farmers are prudent in their use of modern inputs and implement sound management practices based on an understanding of the crops and the environment. This adherence to the fundamentals of sound, efficient and responsible farming is the quintessence of *sustainable agriculture*.

Sustainable agriculture, as defined here, is equally relevant to conventional farmers and organic farmers. The former need to be aware of the limitations and dangers involved in the excessive, careless and irresponsible use of modern inputs; the latter should realize that a blind adherence to prohibitions based on beliefs that have not been scientifically or empirically validated, impose limitations that result in higher production costs, more labour and lower yields.

With *sustainable agriculture*, the differences between conventional and organic farming become irrelevant.

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PART IV

Soil and Crop Management

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CHAPTER 10

Soil Fertility

The concept of soil fertility

There is no generally accepted concept of the term fertility as applied to soils. For our purpose, soil fertility can be defined as the ability of the soil to produce high yields consistently, provided environmental factors such as light, moisture, temperature, etc., are not limiting and crop management practices are efficient.

The nature of soil fertility is, however, more complex than this definition implies; it depends not only on chemical and physical characteristics of the soil, but also on the biological processes resulting from the many and varied activities of the soil organisms. The soil is a very complex medium, in which chemical, physical, and biological activities are proceeding continuously, with many and varied interactions taking place between them.

Under arid conditions, the physical, chemical, and biological processes of soil formation are slowed down considerably. The plant cover is at best diffuse and of low productivity. As a result, rock minerals break down slowly, profile characteristics are not well developed, and soil organic matter and soil nitrogen are always at a low level. Leaching, however, is also at a low level, and therefore there is frequently an excessive accumulation of soluble salts. The 'fertility cycle' under desert conditions is practically a closed system, with nutrients circulating at a very slow rate.

In those cases in which dry-zone soils have characteristics similar to humid soils, these were developed during geological ages when precipitation was higher (Tucker, 1988).

The breakdown and decomposition of plant residues is extremely slow under arid conditions, and nitrification is inhibited. Nutrients may accumulate in the soil during a cycle of more-than-usually dry years, permitting a fairly lush growth when rains do finally occur; this may give a mistaken impression of fertility, as evidenced by the poor growth that is usually obtained when there are two or more good rainfall seasons in succession.

The farmer has a considerable influence on the level of fertility of his soils: practically all agricultural operations affect soil fertility for better or for worse, according

to the way in which they are executed. Tillage can improve soil structure or just as effectively destroy it; chemical fertilizers are one of the most efficient means of increasing the productivity of the soil, but their injudicious use can cause much damage to soil fertility. Irrigation can 'make the desert bloom'; it can, however, also transform fertile areas into deserts, in which even desert plants will find it difficult to establish themselves.

No single factor is capable of raising the fertility of the soil to its highest potential level if other relevant factors are neglected. A discussion of the main factors affecting soil fertility therefore involves a review of most soil characteristics and farming practices.

The primary soil characteristics that affect soil fertility are

- *physical features*: mainly texture and structure, which control the flow and storage of water and the heat exchange, which in turn affects root penetration and water and nutrient uptake;
- *chemical soil properties*: including nutrients as well as harmful elements; exchange capacity and pH, which interact in influencing nutrient availability.
- *biotic aspects*.

Physical factors affecting soil fertility

The physical properties of a soil largely determine the way in which it can be used most effectively. The soil system consists of three, physically separable phases – solid, liquid and gaseous. The solid phase consists of a porous matrix; the pore spaces within the matrix are occupied by the liquid phase (soil 'solution') and the gaseous phase (soil atmosphere).

The matrix consists of mineral and organic particles of various sizes; the relative proportions of mineral and organic components vary considerably in different soils. The mineral component is derived mainly from the weathering of the parent rock and from the breakdown of animal skeletons – providing calcium carbonate and calcium phosphate, both of which are of considerable importance to soil fertility.

The organic component consists of plant and animal materials in various stages of decomposition.

The solid phase

Soil texture

Classification. The relative proportions of different-sized soil mineral particles constitute soil texture, a property inherited from parent material and therefore a rather permanent property of a soil (Thien, 1983). However, surface textures can be changed by erosion, causing removal of top soil and/or deposition of windborne

particles. Texture can also be changed by the downward movement of clay particles from the surface soil (A horizon) to the subsoil (B horizon).

If not excessive, the increased clay content of the subsoil is beneficial: the surface layer is easier to till and less subject to compaction; the water and nutrient storage capacity of the subsoil is increased, and leaching losses reduced. However, if too much clay accumulates in the subsoil, a claypan layer may form, which impedes root penetration (Thien, 1983).

All gradations in size of particles normally occur in a soil. For purposes of classification, it has been found necessary to divide the particles into more or less arbitrary groups known as soil fractions or separates. These are determined by mechanical analysis.

The classification of soil separates used in the USDA Soil Taxonomy is shown in Table 10.1.

These differences in size of soil particles profoundly affect such soil properties as the movement and retention of water, circulation of soil air, adsorption of nutrients, and microbial activity; they also largely dictate management practices such as tillage methods, irrigation methods, choice of crops, etc.

As each fraction has different physical and chemical properties, the physical and chemical properties of a soil will be dominated by the properties of the fraction that is present in the largest amount.

Soils in which large particles (gravel and sand) predominate, do not swell on wetting or contract on drying; they have a very low water-holding capacity, very little capillarity, rapid water infiltration, low retention of nutrients, little or no cohesiveness and plasticity, high specific temperature, and excellent aeration. Soils with predominantly very small particles will swell when wetted, and shrink considerably on drying; they have a very high water-holding capacity, high capillarity, slow infiltration rate, high retention ability for nutrients and gases, considerable cohesiveness and plasticity, low specific temperature, and poor aeration.

A predominantly sandy soil will have good aeration and will be easy to till; but it

TABLE 10.1

Soil texture categories

	Equivalent diameter range (μm)
Very coarse sand (vcoS)	2000–1000
Coarse sand (coS)	1000–500
Medium sand (mS)	500–250
Fine sand (fS)	250–100
Very fine sand (vfS)	100–50
Silt (Si)	50–2
Clay (C)	< 2

will have little inherent fertility and will not be able to retain water or plant nutrients to any large extent.

By contrast, clay soils may have a high potential fertility and considerable ability to retain nutrients and water, but they are apt to become stone-hard when dry, and sticky and poorly aerated when wet.

Predominantly sandy soils do have certain inherent advantages in arid regions – especially when irrigation is to be practised. Their greater permeability to water and lower ability to retain cations, reduce the dangers of their becoming saline. Though their water-holding capacity is lower, the water is far more easily available to plants than in heavy loams and clays – a point that is of importance for rain-grown crops when rainfall is sparse. For these reasons, alluvial sand areas in arid regions always carry more abundant vegetation than do alluvial clay soils, which are also more frequently saline (Kovda, 1961).

Briefly, it can be stated that the texture of a soil is its most permanent characteristic, in contrast with other physical characteristics such as soil structure, which can be rapidly modified – for better or worse – by management.

Standard textural names of soils. Over the years, colloquial terms such as loam, sandy loam, silt-loam, etc., have been used to describe combinations of sand, silt, and clay, in various proportions. An attempt has been made to standardize these names and their meanings, based on a triangular diagram called a ‘textural triangle’ such as is depicted in most textbooks on soil science. This triangle is broken up into twelve areas, with different proportions of sand, silt, and clay – each with its standard, conventional name (Fig. 10.1).

Porosity or pore space. Porosity is the percentage (by volume) of a dry soil that is occupied by ‘air’. Normally the pore space is occupied by gases and water in varying proportions. The *total porosity* is of importance from the standpoint of aeration and moisture storage. The aeration of soils (the exchange between soils and atmospheric gases) occurs mainly by diffusion. The rate of diffusion is proportional to the amount of free pore space – that is, the pore space unoccupied by water.

Crop plants, for their normal development, need a constant and balanced supply of water and air to their roots (Fig. 10.2). These two requirements may be conflicting, since with increasing water supply a deficiency in air supply may arise. This will impair nutrient uptake by the roots, interfere with the proper functioning of many essential physiological processes of the plant, and have an adverse effect on the activities of many groups of beneficial soil micro-organisms. Total porosity and pore size distributions are therefore important parameters of a tilled soil, being relevant to the availability of moisture and air, as well as to the ability of the soil to absorb water rapidly during a heavy rain.

Total pore space alone is a poor measure of aeration. A soil may have a high percentage of total pore space, but if the percentage of clay is excessively high, the

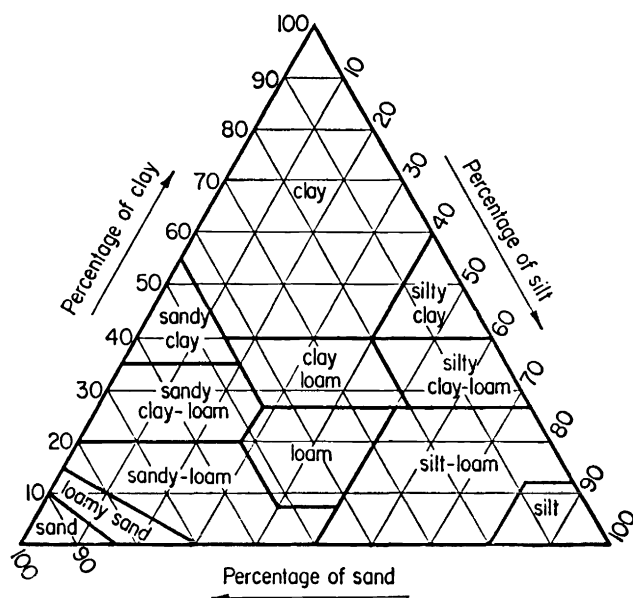


Fig. 10.1. Basic soil-texture classes. By courtesy of the US Department of Agriculture.

pores will be extremely small and all pore space may, under certain circumstances, be filled with water, with a resultant lack of aeration. At the other extreme are the sandy soils, with a large number of very large pores, incapable of retaining water. Air supply in this case is very favourable but plants easily suffer from a shortage of water. The ideal soil will therefore have sufficient pore space, more or less equally divided between large and small pores, the large pores ensuring a free movement of air, and the small pores a good water holding capacity. This can be achieved only if the primary soil particles are aggregated. The size distribution and the interconnections of the pores forming the pore space also have a considerable effect on root growth. The more favourable the pore space distribution is, in particular of the interconnected pores in the 0.1–0.5 mm size range, the greater will be the depths to which the roots can penetrate during dry periods. This is of considerable importance in regions with erratic rainfall (E.W. Russell, 1966).

The proportion of solid to pore space varies greatly among the different types of soils. In general, the greater the content of soil colloids is, the higher will be the percentage of pore space. Total soil porosity in mineral soils ranges from 25 to 60% but most usually is within the range of 40 to 50% (Gardner, 1966).

Porosity and *soil bulk density* are inversely related. Therefore any practice that affects the one, also affects the other. Increased bulk density is undesirable because it is an indicator of soil compaction (Unger, 1990). A compact soil has a poor structure and a small total volume of pore space.

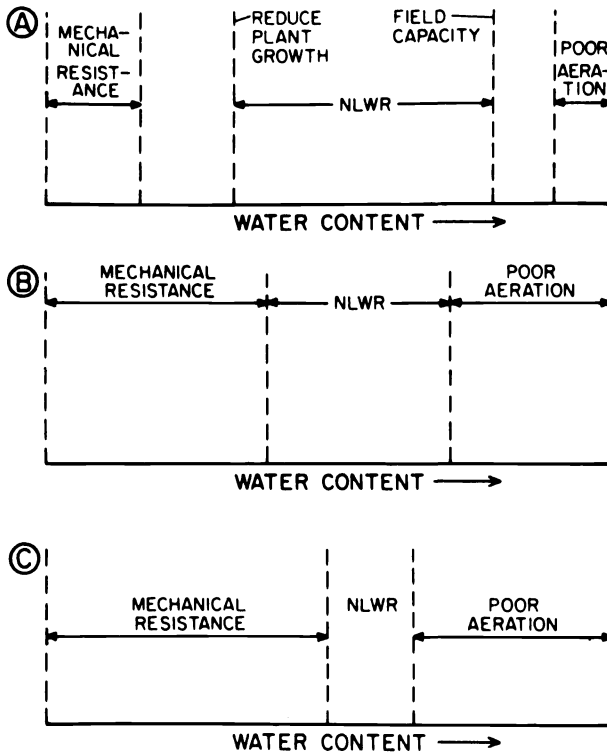


Fig. 10.2. Generalized relationships between soil water content and restricting factors for plant growth in soils with increasing bulk density and decreasing structure in going from case A to C. NLWR = non-limiting water range. From Letey (1985). By permission of Springer, Berlin.

Compaction due to movement of farm machinery has become a serious problem of mechanized agriculture.

Soil structure

Soil structure has a dominant influence on the air and moisture régime of the soil, on its hydraulic conductivity and, consequently, on root growth and soil biological activity. It is therefore an important factor in soil fertility (EUROCONSULT, 1989).

The basic requirement for effective crop production is that the solid phase of the soil should not constitute a compact mass, but is so structured as to facilitate water infiltration, retain moisture, allow free movement of 'air', and promote easy penetration and proliferation of the root system.

Soils that have broken down into a powdery dust by excessive tillage when dry – the classic example being the soils of the Great Plains in the USA – or soils that form a compact mass on drying, such as the alkaline soils resulting from faulty irrigation methods, cannot be a convenient medium for crop production under arid conditions.

Even a soil with good structure will, on drying, form hard, compact clods. However, these clods break down easily under tillage, and the favourable soil structure is easily restored. By contrast, soils with poor structure produce clods which are resistant to normal tillage operations. When wetted, they break down into a plastic mass; upon redrying, the soil is covered with a hard crust. These soils can be tilled only within very narrow limits of moisture content, and are rarely productive.

Soils with a poor or no structure are easily compacted, have poor aeration, low hydraulic conductivity, and resist root penetration. If soils containing clay are ploughed when wet, their structure is destroyed and they become 'puddled'. Puddled soils provide poor seedbeds, and poor stands of crops. Paddy rice production is, of course, an exception to this general rule.

Excessive breakdown of aggregates will also cause severe soil crusting after each rain or irrigation. Aggregates larger than 5–6 mm in diameter leave excessively large pore spaces between them, thereby reducing water holding capacity and preventing intimate contact between the roots and the soil particles. Relatively large aggregates and a rough micro-relief of the soil surface improve water infiltration.

Experience has shown that there is a very close relationship between the fertility and stability of soils and their structure, as expressed by the percentage of stable soil aggregates of desirable size. All farm operations that improve soil structure can therefore be considered as improving fertility, and vice versa.

Formation and stability of soil structure

The ability of aggregates to resist destruction by disruptive forces is called *aggregate stability*.

Aggregate stability is very fragile and difficult to maintain, especially that of arid soils. The particles that form the aggregates are bound by very weak forces; the aggregates break down easily by disruptive physical or chemical forces. Thien (1983) mentions raindrop impact, machinery compaction, dispersion, and oxidative loss of organic binding agents as the most prevalent aggregate destroying factors.

Once the peds are broken, the finer particles fill pores and seal the surface of the soil, a process called puddling. When the soil surface dries, hard impermeable crusts are formed.

The most stable aggregates are formed when the active surface of these particles has a high saturation of Ca ions, and stability is further increased by the cementing effects of gummy organic substances in the top soil and sesquioxides or calcareous compounds in the subsoil (EUROCONSULT, 1989).

The mineral binding substances are of particular importance in tropical and sub-tropical soils, where stable aggregates cemented by iron ensure high water infiltration rates.

The organic binding substances are derived from the activities of soil fauna and flora through their feeding and other activities on plant residues (Unger, 1990).

Humic acids and polysaccharides resulting from the breakdown, by micro-organ-

isms, of soil organic matter and dead microbial cells, are sources of adhesive materials which surround soil particles, and may also have an electric charge; they are therefore capable of binding the soil particles together. These substances are not entirely resistant to further breakdown, so that a constant supply of such adhesive substances is necessary for maintaining soil structure (Lynch, 1983).

Fungi also bind particles together by the mycelium filaments that they produce. Thus micro-organisms are probably the major determinants of soil structure.

Generally, the most important crumbs are produced by fungi; these crumbs are about 2–4 mm in size and are resistant to crushing. The crumbs produced by actinomycetes are slightly smaller, and also resistant to crushing; bacterial-produced crumbs are compact, less than 0.5 mm, and are fragile (Harris et al., 1966).

In a productive soil, improving structure is a gradual process, resulting from the activities of living organisms. In infertile soils, such as alkali soils, whatever structure exists, is mainly due to abiotic forces (Jacks, 1963).

Factors affecting soil structure

Kinds of clay. The influence on structural stability of clay particles in the soil is determined mainly by the kind of clay and the kind of exchangeable ions which predominate on their surface. The most marked effects, in this respect, are exercised by calcium and sodium ions.

Calcium-saturated clay, on drying, forms small, friable but water-stable clods with numerous cracks. When rewetted, the calcium prevents deflocculation, the peds swell but do not break down easily.

By contrast, soils in which the clay is saturated with sodium forms large, hard, compact clods on drying, with very few cracks. When these clods are rewetted, the sodium deflocculates the clay, and the clods break down into a plastic, formless paste.

Environmental factors. Experimental results indicate that micro-organisms produce better aggregating substances at relatively low temperature, resulting in a more stable structure. As temperature increases from 10 to 55 °C, the soil-aggregating influence of organic residues was found to decrease. On the other hand, with increasing temperatures, less time is required for maximum aggregation to occur, but it is less stable (J.P. Martin and Craggs, 1946). It is assumed that the microbial population which is active at lower temperatures produces more effective aggregating substances than the organisms operating at higher temperatures, whilst the higher temperatures simply favour a more rapid decomposition of organic matter. In waterlogged soils, the rate of aggregation is considerably reduced, indicating that anaerobic organisms produce few aggregating substances, and that these are of low quality (J.P. Martin and Craggs, 1946).

In high-sodium soils, the addition of organic residues causes much less aggregation than in normal soils; probably the sodium disperses the inorganic soil colloids and

the aggregating substances formed by the micro-organisms (Aldrich and Martin, 1954).

Soil fauna. Burrowing and digging animals, and a great variety of insects and worms, have a considerable effect on soil structure. The most widely known and the most ubiquitous in moist climates are the earthworms, whose considerable role in improving soil structure was stated already by Darwin. However, their numbers are far smaller, and their effects of little significance, in the hot arid climates.

In areas with sparse vegetation, as in the semi-deserts and along their fringes, ants and termites, by burrowing in the soil, can be as effective in improving soil structure as the earthworms are in the humid regions (Hopp and Slater, 1948). They break up the larger and coarser conglomerates mechanically; they digest organic matter and contribute various enzymes to the residues which affect their further decomposition (Pauli, 1967).

Grazing animals. Grazing animals may accelerate the fertility cycle considerably by increasing the rate of decomposition of plant residues following the return to the soil of faeces and urine and the resulting increased microbial activity. If, however, over-grazing occurs, plant residues and hence soil organic matter decrease; this results in increasing erosion from the denuded soil which in turn, further impairs the soil structure.

Crops. When virgin soils that had been covered by perennial grasses are brought under cultivation, soil structure usually declines rapidly. The rate of decline depends to a large extent on the kind of crops grown.

Crops may have diverse affects, both direct and indirect, on soil structure. Thus a more favourable and stable soil structure forms under perennial crops, in particular grasses, than under annual crops that are grown in rotation.

In the Great Plains region of North America it was found that cropping systems consisting of continuous small grain, continuous row crops, or cereal cropping alternating with fallow, showed a loss of approximately 80% of the initial aggregation of the virgin buffalo grass range after approximately 40 years of arable cropping. On the other hand, seeding arable soil to buffalo grass doubled the amount of aggregation within five years (Olmstead, 1946). In South Africa, the structure of a soil that had been cropped continuously for 20 years was restored by a grass cover after seven years (Hyam, 1950).

Plant residues also supply organic matter to the soil. The relationships between plants, organic matter, and soil micro-organisms, were clarified in experiments carried out in the arid climate of New Mexico (J.P. Martin and Craggs, 1946). No aggregation of soil particles occurred in a sterilized soil in which roots of sudan grass proliferated. After inoculation of the soil by micro-organisms, small aggregates were formed which were subsequently bound together into larger aggregates by the rootlets of the sudan grass.

Microscopic examination of soil aggregates confirms that the smaller aggregates are formed by the cementing together of soil particles by colloidal materials, whilst

larger aggregates are formed by the binding action of mycelia of fungi and rootlets of higher plants. However, the main effect of crops on soil structure may be indirect and dependent on the amount of tillage involved. Perennial crops with little or no tillage have the best effect, closely planted crops with little inter-row cultivation do relatively little harm to soil structure, whilst the greatest damage to soil structure is caused by widespaced crops with frequent inter-row cultivation, such as maize and cotton.

Tillage operations. The properties of clay change at different degrees of wetness. A dry clay is hard, compact, and breaks into clods with ploughing. If the clay is wetted gradually, the water molecules at first are adsorbed on the surface of the clay particles, acting as a lubricant and allowing them to slip easily against one another. The clay becomes soft and the clods break down easily. This is the ideal stage for tillage. If more water is added, the plasticity of the clay increases, it becomes sticky, and is then easily transformed by pressure into a plastic mass.

The moisture content at which a clay soil, on drying, ceases to stick to a metal rod pressed into the soil, is called the 'sticky point', and is optimal for tillage operations. For then the soil does not stick to the tillage implements and a minimum of damage is caused to soil structure by compaction. The pressure exerted by tillage equipment may even increase aggregation. However, any beneficial effects may be easily lost by subsequent tillage operations, such as disking, levelling, rolling, etc. If carried out in dry soil, these operations reduce a large proportion of the aggregates into fine dust; if the soil is wet, compaction and reduced pore space result.

The inhibition of root growth in compacted soils is not caused by mechanical impedance only; in dry soils the decrease in soil water potential, and in wet soils the lack of air and the accumulation of phytotoxins contribute to a decrease in root extension (Marschner, 1986).

Rainfall and irrigation. Raindrops hit the soil surface with considerable mechanical force, and can rapidly destroy the structure of the upper soil layer, creating a hard crust. This crust effectively seals the soil surface, and reduces the depth of water penetration and aeration. The overall effect of rainfall is therefore similar to the detrimental effects of tillage, the main difference being in the depth of the soil layer that is compacted.

Ellison (1952) has calculated that, for a rainfall of 75 mm per hour, the raindrops falling on one acre have a compacting effect on the soil that is equivalent to 29 average farm-tractors working on this area during the time of the rainfall!

The impact of raindrops against the soil destroys the aggregates in the surface soil, while the run-off water becomes turbid with suspended particles which clog the pores of the upper layers; thereupon permeability further decreases, with a concomitant increase in erosion damage (Vershinin et al., 1959).

In South Australia, on a red-brown soil, the principal damaging effect of excessive rainfall in the month following sowing was found to be an increase in apparent

density, which amounted to 0.052 g/cm^3 for each additional inch of rainfall. The corresponding decline in grain yields was approximately 680 kg/ha for each increase of 0.1 g/cm^3 in apparent density (Millington, 1961).

Irrigation by surface methods (flooding, furrows, etc.) acts in a different way. After each irrigation, there is a considerable excess of water in the upper soil layer, during the 24–48 h required for an equilibrium to be established until the soil reaches its full water-holding capacity. This excessive humidity can cause the breakdown of soil aggregates that are only partially stable, thereby compacting the soil.

The gaseous phase

In freely draining soils, the large soil pores cannot retain water even at field capacity, and are filled with air; as the roots withdraw water, fresh air also occupies the smaller pores. In soils with good structure, air content is therefore usually maintained at 15–20% by gaseous diffusion, and supplies of oxygen are adequate for root growth and metabolism (E.W. Russell, 1973).

Composition

The composition of soil 'air' is not markedly different from that of the free atmosphere, the only important difference being that the former is normally richer in carbon dioxide. However, the carbon dioxide content of the soil 'air' is far from constant. Additions of organic matter to the soil usually result in a rapid increase of carbon dioxide and a parallel decrease of soil oxygen; root respiration has similar effects. Oxygen deficiencies and excessive CO_2 in the root atmosphere have a depressive effect on the growth of most crop plants and their associated micro-organisms (Grable, 1966).

Carbon dioxide becomes toxic at concentrations above 1% in the soil 'air'. Frequently, the toxicity of the carbon dioxide is more lethal to the root system of plants than is the relative lack of oxygen. When the oxygen content of the soil 'air' falls to below 10%, this usually results in damage to the root system. When the level falls to 3%, the roots of most cultivated plant species die (Grable, 1966). Soil 'air' usually contains sufficient oxygen for the vital processes of the plant and soil micro-organisms, but air as a whole may be in short supply in soils with a poor structure or those which are excessively wet.

Focht and Martin (1979) stress that it is the dissolved oxygen concentration, and not the gaseous oxygen concentration, that is the factor governing the transition from aerobic to anaerobic respiration by micro-organisms, so that data relating to the former can be misleading.

Anaerobic conditions

Under waterlogged conditions, the escape of CO_2 and renewal of the air supply ceases, and as a result undesirable biological activity occurs which may engender

toxic concentrations of methane, hydrogen sulphide and other substances, as well as loss of nitrogen in gaseous form (N_2O or N_2) as a result of denitrification.

The anaerobic decomposition of organic matter also releases various toxic substances (especially carboxylic acids) and ethylene, a growth regulator (R.S. Russell, 1977). Meanwhile, root respiration, which is essential for certain metabolic processes, is adversely affected, nutrient and water uptake being thereby curtailed.

Certain crops, such as rice, are capable of growing normally in inundated soils. As with other plants, their roots require oxygen for their normal functioning, but the oxygen in this case is absorbed by the aerial parts of the plant and transported to the roots through continuous intercellular spaces in the stems and roots (Barber et al., 1963).

Part of the carbon dioxide in the soil combines with water to form carbonic acid (H_2CO_3). This is a weak acid which is nevertheless capable of dissolving certain mineral components of the soil and thereby making them available to the crop.

In fertile soils that are rich in organic matter, and with a favourable moisture régime, soil micro-organisms free very large amounts of carbon dioxide. There is therefore a direct relationship between soil fertility and the amounts of carbon dioxide liberated from the soil.

The need for oxygen and the parallel sensitivity to excess carbon dioxide in the soil 'air' increase with increasing temperatures; these factors are therefore more critical in the hot arid areas than in the humid regions. The greater sensitivity to lack of oxygen at higher temperatures may be due to the increased intensity of respiration of roots (Vershinin et al., 1959), or to the diminished solubility of oxygen in soil solutions at higher temperatures.

Anaerobic conditions occur in vast regions in the world where fields are periodically flooded by irrigation. Over-irrigation may cause temporary waterlogging, with resultant damage to crops. Leakage from irrigation ditches may cause waterlogging throughout the irrigation season (Krizek, 1982). Waterlogged soils are a major factor in land areas lost to production as a result of irrigation, a problem discussed in Ch. 13.

Chemical soil fertility

There are two types of chemical fertility: potential and actual. *Potential fertility* refers to "the capacity of the soil to supply nutritive elements from its inorganic and organic reserves through the processes of, respectively, weathering and microbial mineralization"; *actual fertility* is "the rate at which nutritive elements become available to the crop" (EUROCONSULT, 1989).

The nature of the parent material of the soil, and the processes of weathering, determine the potential reservoir of plant nutrients.

The limited leaching to which arid soils have been subjected has resulted widely in

the accumulation of mineral substances; these soils are therefore generally rich in calcium, potassium, magnesium, sodium, phosphorus and sulphur, and deficiencies of micro-elements are rare in them. However, the virtual absence of leaching has also resulted in many cases in the accumulation of salts that are detrimental to plant growth, such as chlorides and carbonates of sodium and magnesium.

Soil reaction – pH

Soil reaction is generally expressed by pH, a numerical designation of relatively weak acidity or alkalinity in soil, as determined by the relative proportion of hydrogen and hydroxyl ions present. Because the H^+ is relatively low in soils, it is expressed as the logarithm of the reciprocal of H^+ concentration in solution (Mengel and Kirkby, 1982).

The soil reaction has a profound effect on many factors which determine the suitability of a soil for crop growth.

For most crops and soil micro-organisms, a pH of 6.0–7.5 provides optimal growth conditions. Beyond that range, crop species, and even varieties, may differ in their tolerance to alkalinity or acidity.

The use of pH to define soil conditions has serious limitations: accurate measurement of the pH of the soil is difficult, the correct interpretation of the measured pH is difficult, the pH varies considerably over a field at a given time, and it is changing constantly with time (E.W. Russell, 1973).

Alkalinity (pH > 7)

The calcium content of the soil is a major factor influencing soil pH.

In regions of low rainfall, the colloidal complex of the soil is generally dominated by the common basic cations – calcium, magnesium, and sodium. The colloidal complex will tend to remain high in adsorbed calcium ions as well as in other basic cations, and the soil solution will remain alkaline. In such soils, variable quantities of soluble bicarbonates, carbonates, biphosphates, and silicates, are often found which, upon hydrolysis and dissociation, yield hydroxyl ions in excess of hydrogen ions. As a result, calcareous soils may have reactions ranging from neutral to very alkaline (pH 7–11).

Moderately alkaline and neutral soils are usually very fertile; in alkaline and neutral soils, 2:1 layer clay minerals (especially montmorillonite) predominate; they are usually adequately supplied with Ca, Mg, and K.

However, in dry alkaline soils high amounts of Na are retained. If the groundwater is not too near the soil surface, and irrigation is properly managed, the sodium salts are leached beyond the root zone and are not harmful to crops; otherwise, the salts may accumulate in the surface soil and interfere with crop production.

Excessive alkalinity occurs quite frequently in the dry regions and may have the following undesirable effects:

- Toxic effects on the root system.
- Various nutrient deficiencies may occur: excess Mg may limit uptake of Ca; in the presence of vermiculite clays, K may be strongly fixed. N, P, and S are frequently deficient; levels of Fe are generally high, but generally in unavailable form (R.B. Clark, 1982).
- Certain desirable activities of micro-organisms may be inhibited; a problem that may occur in alkaline semi-arid zone soils is the transient inhibition of nitrification caused by the toxicity of free ammonia to *Nitrobacter*, resulting in the build-up of nitrite, which may have detrimental effects on plant growth (Focht and Martin, 1979).

Only few crops do well at pH values < 7.5. Relatively tolerant of alkalinity in the range pH 7.6–8.0 are: cotton, sugarcane and wheat (EUROCONSULT, 1989).

Acidity (pH < 7)

Though most dry-zone soils tend to be more or less alkaline, and excessive acidity is a rare occurrence, a considerable number of agricultural soils in the southwestern United States and elsewhere are slightly acidic (Focht and Martin, 1979).

In the dryland tropics, soil acidity is a widespread limitation in extensive areas of South America, Asia, and Africa. Where shifting cultivation is practised, the liming effect of the ash has a mitigating effect on acidity, which, however, is effective for only one to two years of cropping (Buol and Sanchez, 1988).

A major problem in dryland areas in West Africa, is the acidity of the surface soil, often increased by the decomposition of crop residues applied as mulch (Pieri, 1987).

In acid soils, K^+ ions are easily displaced from the exchange complex and lost by leaching; N availability is low because of reduced microbial activity.

Below pH = 4.0–4.5, mineral soils contain so much Al^{3+} as to be severely toxic; Mn and Fe may also be present at toxic levels. Below pH = 3.0, H^+ ions are toxic to most plants.

Crops that do well on soils with pH values lower than 6.0 include potatoes (4.8); rice, sorghum, millet, cotton, pineapple, cowpea, sweet potato, crotalaria (5.0); maize, tobacco, groundnut, eggplant, tomato, cabbage (5.5). (Focht and Martin, 1979).

The soil solution

The concentration of mineral nutrients in the soil solution is an indicator of the mobility of the nutrients towards the root surface as well as vertically, and is a measure of the *intensity* of supply of mineral nutrients. It is therefore an important component of soil fertility.

The buffer power of the soil determines the degree and the rate of replenishment of nutrients from the solid phase into the nutrient solution. It therefore represents the

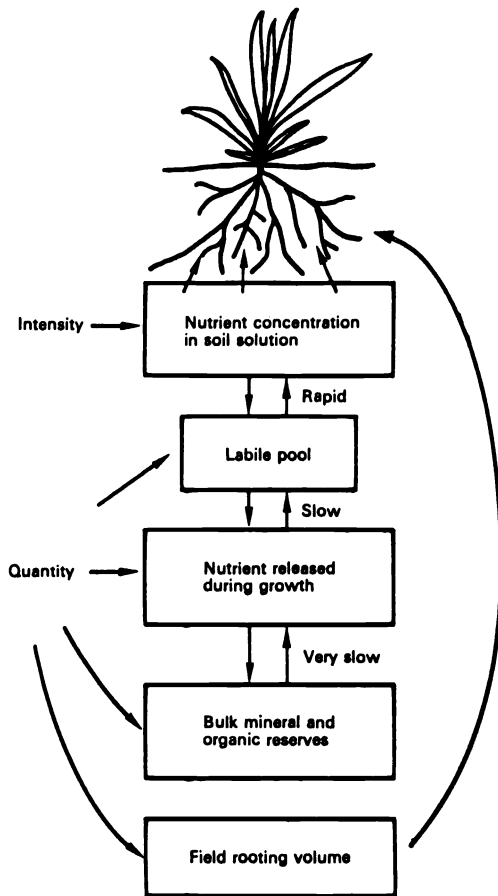


Fig. 10.3. Intensity, quantity, and nutrient sources. After E.G. Williams, from Mengel and Kirkby (1982). By permission of the International Potash Institute.

capacity of the soil to gradually release plant nutrients; consequently, the exchange complex of the soil can be considered as a reservoir that buffers the ionic supply by soil minerals and fertilizers and the ionic withdrawal by crop uptake and by leaching (EUROCONSULT, 1989) (Fig. 10.3).

Since nitrates are generally not adsorbed on the solid phase, their concentration in the soil solution is not buffered and is subject to considerable fluctuation (Marschner, 1986). In contrast to nitrate, phosphate interacts strongly with clay minerals, and its concentration in the soil is buffered by the soil.

The concentration of phosphate actually in the soil solution is usually low, and is practically independent of the moisture content of the soil. The availability of phos-

phorus to the crop will therefore depend on the speed with which the phosphorus removed from the soil solution is replaced from the soil reserves.

An exchangeable equilibrium is established between ions held by the exchange complex of the soil and the soil solution; ions migrating between the two phases form what is called 'the labile ionic pool' (R.S. Russell et al., 1961). As ions are taken up by the plant from the soil solution, this equilibrium is upset; new equilibria are then established by ions moving from the surfaces into solution.

The soil solution is therefore the intermediary whereby nutrient ions move from the soil into the plant, and the rate of uptake of a nutrient is a function of the concentration of the ion in the soil solution.

The availability of nutrients to plants is controlled by the following factors:

- (1) The concentration of ions in the soil solution, which depends on the nature of the colloidal fraction and on the degree of their base saturation.
- (2) The influence of one adsorbed ion on the release of another from the colloid surface. Polyvalent ions are held more strongly than univalent ions; hence, when the soil colloids hold large amounts of potassium and NH_4^+ in proportion to the amounts of calcium and magnesium, the former will be replaced more easily than the latter and therefore plant deficiencies of calcium or magnesium may develop (Tisdale and Nelson, 1975).

By contrast, practically all the nitrate and chloride present in the soil are in the soil solution, so that the concentration of these anions varies inversely in relation to soil moisture content (E.W. Russell, 1973).

Whereas in humid regions the soil solution is very dilute (E.W. Russell, 1973), the situation is entirely different in the irrigated soils of the arid and semi-arid lands, in which calcium and sodium salts, in particular, accumulate. Under these circumstances, the osmotic potential of the soil solution may have an appreciable effect on crop growth – especially with increasing soil moisture tension.

Nutrient elements in the soil

Nitrogen

The primary source of soil nitrogen is the inexhaustible supply obtained directly or indirectly from the atmosphere. The amount of nitrogen in the ploughed layer of cultivated soils usually ranges from 0.02 to 0.4% by weight (Black, 1968).

Most of the nitrogen in the soil is in organic form; it is generally assumed that organic matter contains about 5% nitrogen, of which only a fraction becomes available yearly. The rate at which N becomes available depends on the rate of mineralization of the organic matter.

The total amount of nitrogen in the soil is therefore not an indication of the amounts of this nutrient which are immediately available to a crop, but constitutes a

reserve from which nitrogen may become available to plants – and not necessarily at a rate commensurate with the requirements of an actively growing crop.

The percentage of nitrogen in the soil tends to remain constant at a level which depends on the nature of the parent material, on the leaching characteristics of the soil (mainly determined by its texture), and on the management system adopted (Cooke, 1967).

Phosphorus

Soil phosphorus is present in the soil in mineral and organic forms, usually in amounts far lower than those of nitrogen and potassium, and varying from 0.1 to 0.4% while rarely exceeding 0.5%. The quantity of phosphorus in the soil solution is always small, usually ranging from 0.1 to 0.5 mg/l in most soils. A level of 1 mg/l of P in the soil solution is generally considered adequate for plant growth (Seatz and Stanberry, 1963).

In low-rainfall areas, the generally calcareous nature of the soils results in the formation of apatites, calcium phosphates being the major mineral P compounds. The contribution of organic compounds containing P will be mentioned in the section on biotic soil activities.

At low concentrations of soil phosphate, the supply of P is insufficient for the requirements of plants and soil micro-organisms and competition occurs. Bacteria in the rhizosphere assimilate labile inorganic P and P uptake by plants is thereby restricted; the microbes are attacked by bacteriophagous amoeba, and the bacterial P is subsequently returned to the phosphorus pool after mineralization.

Total phosphorus levels tend to be low in the frequently alkaline semi-arid soils, but available phosphorus tends to be higher than in acid soils. As organic P levels are reduced by cropping, P deficiencies become widespread (Tucker, 1988).

Where intensive cropping, including P fertilization, has been practised for a number of years, the phosphorus content of the soil has generally been built up, frequently to a level at which farmers can stop using P fertilizers for a number of seasons without loss of yield (NRC, 1989).

Potassium

Of the major macro-nutrients, potassium is usually the most abundant in soils. In particular in dry regions, the presence in the soil of small fragments of little-weathered K-bearing primary minerals provides a considerable reserve of potassium.

The natural potassium reserves of semi-arid soils may however become depleted by cropping and the removal of crop residues. Many coarse-textured soils are poor in K because they lack the K retention mechanism. In tropical dryland zones, about one-third of the area has low K reserves (Buol and Sanchez, 1988).

Potassium occurs in the soil in a number of forms, though most of it is apt to be unavailable to plants even after years of cropping:

(a) *Water-soluble* – the potassium which is present in the soil solution. This is a very small fraction of the total, and even in fertile soils this form cannot supply the major requirements of a crop.

(b) *Exchangeable* – the potassium which is held by the exchange fraction of the soil. This is the important reservoir of readily available potassium, though together with water-soluble potassium it represents only a small part – commonly 1–2% – of the total potassium of the soil (Arnold, 1960).

(c) *Non-exchangeable* but slowly available potassium. This comprises the native soil potassium from partly weathered minerals and forms the reserve from which the water-soluble potassium of the soil solution is gradually replaced; it therefore constitutes an essential element of the permanent fertility of the soil. The higher the temperature is, the greater will be the release of non-exchangeable K (Burns and Barber, 1961). Residual potassium from fertilizers is also in this form. The slowly available forms amount to 1–10% of the total soil potassium (Tisdale and Nelson, 1975).

(d) *Inert* – present in the unweathered potassium-bearing parent minerals, and released at an extremely slow rate.

These groupings are somewhat arbitrary and the boundaries between them are not sharply delineated. The different forms are in equilibrium: as potassium is removed from the soil by plants and by leaching, a transfer occurs from the slowly available forms; on the other hand, especially after applications of large amounts of potassic fertilizers, some of the potassium may revert to slowly available forms.

The alternating drying and wetting of the soil, characteristic of irrigation agriculture, usually causes an increase of exchangeable potassium when the levels of soil potassium are low to medium. When the levels are high, the opposite may occur, though the reasons for this last phenomenon are not yet known (Tisdale and Nelson, 1975).

Calcium

The calcium content of soils varies more than does that of any other element. Calcium is a constituent of a number of primary rocks and minerals, etc., which fall into the five groups: (a) calcium present in the mineral particles, which are nearly all of primary rock; (b) calcium carbonate, in general the most important source of calcium in soils; (c) calcium sulphate; (d) simple salts of calcium in the soil solution; and (e) exchangeable calcium.

Carbonate of calcium (CaCO_3) occurs alone or often with magnesium in many arid regions (calcareous soils). Concentrations of calcium sulphate are found only occasionally in some arid soils (gypsum soils), though beds of gypsum occur in numerous places. The most important form of calcium in soils as a whole is that associated with the exchangeable colloidal complex. Exchangeable calcium is considered readily available.

Calcium produces several specific effects, which result in the improvement of soil

structure and in increased crop production. The leaching losses of calcium from soils depend on the quantities of calcium present, the forms in which they are held, the amount of percolating water, and the production of carbonic acid. In humid climates with high rainfall, leaching is active and the removal of calcium ions from the colloidal complex results in their substitution by hydrogen ions. In arid climates sodium ions frequently replace calcium ions on the colloids, yielding soils of poor physical condition.

Magnesium

There is usually a very close relationship between calcium and magnesium in the soil. Magnesium carbonate is usually found in mixtures with calcium carbonate – particularly in dolomite ($\text{CaCO}_3 \cdot \text{MgCO}_3$). Magnesium deficiencies are in general rare in arid-land soils; fine-textured soils formed from parent rock with high magnesium content may contain several percent of this element (Tisdale and Nelson, 1975).

Sodium

Large amounts of sodium may accumulate in the soils of arid and semi-arid regions. The significance of sodium accumulation will be discussed in Ch. 13.

Micro-nutrients

Deficiencies of micro-nutrients in arid zones are rare; however, in many soils which were originally considered as unproductive, it was found that a deficiency of one or more minor elements was the sole cause of their apparent infertility. Copper, zinc, and molybdenum deficiencies were identified in Australia, and supplying these elements in minute quantities transformed a previously infertile, valueless soil into a normally productive one.

Soil-induced deficiencies

The availability of soil plant nutrients may be influenced by certain soil conditions, ionic interactions, and microbiological activities causing nutrient deficiencies (EUROCONSULT, 1989).

Examples of such soil-induced deficiencies are:

- The effect of pH on availability (cf. p. 460).
- Microbial N fixation when C/N ratios are high (cf. p. 476).
- K fixation and the permanent occlusion of K in the lattice structure of expanding clay minerals, enhanced by NH_4 ions, and reduced by Na ions.
- Antagonisms between Ca and K; between K and Mg (cf. Ch. 11).
- In aerated soils the solubility of Fe depends on the formation of chelated Fe, which is derived from soil organic matter, micro-organisms, and root exudates. The application of farmyard manures to calcareous soils is therefore effective in increasing iron uptake by species with low Fe efficiency (Mathers et al., 1980).

Biotic aspects of soil fertility

Soil micro-organisms

The soil habitat teems with a diverse range of micro-organisms, with their associated enzymes and free enzymes (Lynch, 1983) whose abundance and considerable activities justify the term 'living soil'. This community of micro-organisms is in continuous fluctuation with each change in environment; nutrient supply is a major factor for change, favouring some species which multiply rapidly at the expense of others, but always tending to return to a state of equilibrium (Curl and Truelove, 1986).

Soil microflora

Bacteria. Bacteria are the most numerous micro-organisms in the soil, and are the most responsive component of the microflora to growth-stimulating substances excreted by roots. The most consistently abundant species in the vicinity of roots (the rhizosphere, cf. p. 482) are *Pseudomonas* spp.; other relatively common species are *Agrobacterium* and *Achromobacter*. Other important bacteria are those involved in biological dinitrogen fixation (*Rhizobium*, *Azotobacter*, *Clostridium*, *Azospirillum*), and nitrifying bacteria (*Nitrosomas*, *Nitrobacter*).

Actinomycetes. Actinomycetes are best known for antibiotic production and the inhibition of other soil micro-organisms, especially root pathogens.

Most actinomycetes belong to three genera, but the most common is *Streptomyces*.

Algae. Most soil algae are typically photoautotrophic, and should therefore thrive best in the presence of a light-energy source and CO₂ for carbon. Some species of green algae (*Chlorophyceae*) and blue-green algae (*Cyanophyceae*) can also grow heterophytically, utilizing the oxidation of organic compounds instead of a light-energy source (Alexander, 1977).

Fungi. Fungi are the dominant component of the soil biomass to which they can contribute up to 70% by weight.

Among the agriculturally important fungi are those involved in mycorrhizal associations (cf. p. 495) and the pathogenic species *Phytophthora*, *Pythium* and *Rhizoctonia* (cf. p. 497).

Soil fauna

The soil microfauna includes nematodes, generally by far the most numerous group, followed by mites, collembola, enchytraeid worms, molluscs, earthworms, larger myriapods, beetles, dipterous larvae, spiders, ants and isopods (Macfadyen, 1957).

Small fauna in the rhizosphere can indirectly influence nutrient availability and uptake. By feeding on the microflora, they reduce the soil population active in miner-

alization of nutrients (cf. p. 474) but at the same time they liberate nutrients immobilized in microbial cells (Curl and Truelove, 1986).

Soil macrofauna in desert soils is sparse, but consists of specially adapted species which can withstand drought and can take advantage of the small and occasional amounts of moisture provided by dew or rain to breed. The main species are ants which feed on seeds or decaying wood; sand roaches that are able to absorb water vapour from the soil atmosphere, with relative humidity as low as 28%; tenebrionid beetles that feed on plant residues, and a number of predators: carabid beetles, antlions and centipedes. In irrigated soils, the most important elements are earthworms, collembola, mites, nematodes, etc. (Ghabbour, 1977).

Protozoa. Protozoa mainly comprise amoeba and flagellates, and a smaller number of ciliates. The latter, however, predominate in the cactus rhizosphere in desert soils. The largest populations of protozoa occur in warm, moderately moist soils and are therefore favoured by irrigation (Curl and Truelove, 1986).

Bacteria are the major source of food supply for protozoa. Giant soil amoebae, such as *Arachnula impatiens* are being studied as potential biological control agents (Old and Patrick, 1979).

Nematodes. Most soil nematodes are free-living forms feeding superficially on underground parts of plants or on other soil organisms. Plant parasitic forms will be discussed in Ch. 18.

Nematodes are generally most abundant in the upper 30 cm of the soil layer, but can be found at greater depths in sandy soils. Monocultures of many crops result in the build-up of specific nematode species (cf. Ch. 16).

Micro-arthropods. The most common are mites (*acarî*) which include predatory species, feeding on nematodes and insect eggs as well as detritus feeders and fungivores. *Collembola* are found mostly in the upper soil layer; the two species *Proisotoma* and *Onychiurus* feed on fungi (Wiggins et al., 1979).

Agricultural practices and crop species influence populations, species composition and distribution patterns of mites and collembola. Monoculture, and certain types of long-term crop rotations may favour certain species over others (Wiggins et al., 1979).

Factors affecting populations of micro-organisms

The composition of the population of soil organisms and their numbers are influenced by food supply, plant type, soil type and treatment, environmental factors (light, temperature, moisture, pH) and interactions between the micro-organisms (Curl and Truelove, 1986).

Food supply

The soil population may fluctuate hourly, both in numbers and composition as food supply changes. The addition of organic matter to the soil, combined with favourable conditions of temperature and moisture, makes possible an enormous increase in numbers in a very short time; these disappear just as rapidly when the food supply is exhausted or the environment becomes otherwise unfavourable.

Plant type

Plant species differ in their metabolism, their growth vigour, their root system and, in particular, in the nature and quantity of exudates the latter excrete. All these can affect the population of soil micro-organisms and their activities. Legumes, for example, generally induce a greater proliferation of bacteria than non-legumes. A young plant is first colonized by micro-organisms that happen to be in the vicinity of the roots; as the plants develop, a species-stable population becomes gradually established in the rhizosphere (Curl and Truelove, 1986). Joffe (1969) observed that in groundnuts the ratio between the mycoflora of rhizosphere and root-free soil was greatest when the plants are in the flowering stage, declines during seed formation, and rises again at maturity. These fluctuations probably represent changes in competition for photosynthates between stems, reproductive organs and roots and the resultant exudates affecting the microflora.

There are also differences between various genotypes of the same species in how they affect microbial populations on, or near the roots. This is mainly the case for disease-susceptible in comparison with disease-resistant genotypes regarding populations of pathogenic bacteria or fungi. Genetic differences between cultivars provide some degree of plant control over the microbial environment (Neal et al., 1973).

Soil type

Temperature and moisture conditions are closely related to soil texture, depth, and slope; these factors therefore have a considerable influence on soil organisms. Conversely, microbial activity in the soil, such as aggregation of soil particles causing changes in soil structure (cf. p. 453), or decomposition of organic matter with its multiple effects, influences soil properties.

In a study on soils in Israel on which groundnuts had been grown, Joffe (1969) found that species of *Aspergillus* were most frequent in a light clay soil, *Fusarium* in a loamy sand and species of *Penicillium* in a sandy soil. Heavy soils, especially if they are rich in organic matter, are often richer in their bacterial and actinomycete flora than soils of lighter texture (Palti, 1981).

Chlamydospores of some VA mycorrhizal fungi tend to be more prevalent in loamy than in sandy soils.

Focht and Martin (1979) point out that the microbial flora of semi-arid agricultural soils is basically similar to that of other agricultural soils. Therefore, the basic principles of microbial ecology are equally valid in the soils of the dry and the humid

regions, and the many geochemical processes catalyzed by soil micro-organisms appear to be universally distributed.

The major difference in microbial activity between soils of dry climates and of humid, temperate climates, is due to the greater rate at which biochemical processes occur at high temperatures and in alternating wet and dry conditions.

Agricultural practices and climate determine which micro-organisms are active at a given time and the intensity of the resultant changes in the biological, physical and chemical environment of the soil (Abbott et al., 1988). An understanding of how agricultural practices affect the level of activity of beneficial organisms in the soil, can be relevant to the maintenance and improvement in soil fertility.

Soil treatments

Soil treatments, such as chemical and solar sterilization of the soil, drying the soil, applying fertilizers and other agro-chemicals, can have a more profound qualitative and quantitative effect on the soil inhabitants than soil types. These effects are dealt with in detail elsewhere in this chapter.

Environmental factors

Light by its effect on photosynthesis and plant growth indirectly influences microbial behaviour in the soil.

Soil temperature varies with plant cover, soil moisture and soil depth and is probably the most biologically significant physical variable in the soil. The effect of temperature on root growth and exudates is probably more significant than the direct effect on the micro-organisms. (Curl and Truelove, 1986).

Soil moisture has a marked influence on microbial behaviour and proliferation in the soil, either directly, or indirectly through the influence of soil moisture potential on plant growth (Curl and Truelove, 1986).

Micro-organisms are far less affected by water stress than plants. Few crop plants survive when the soil water potential is below -15 bar, while many fungi and bacteria can thrive at far lower levels; the fungi and actinomycetes being even better adapted to dryness than the bacteria, and at least -30 to -100 bar are required to prevent the growth of many fungi and actinomycetes (Focht and Martin, 1979).

Water requirements for growth and survival of different micro-organisms vary considerably. The moisture régime of the soil therefore has a selective effect on the total soil microflora. With decreasing water potentials, fewer organisms are generally able to grow and reproduce. Bacteria are most active under wet conditions, and their activity is reduced at -3 bar and considerably inhibited at about -15 bar (F.E. Clark, 1947). Some fungi survive in soils at far lower water potentials. Apparently, bacteria are antagonistic to fungi in wet soils, while the fungi may escape antagonism under dry conditions, which are unfavourable to bacteria (Cook and Papendick, 1970).

As soil moisture decreases from field capacity to the wilting point, there is a parallel decrease in the number of bacteria in the bulk soil. However, plants often respond

to water stress by an increase in exudation of amino acids and other nutrients from roots, so that higher bacterial populations may be stimulated in the rhizosphere in drier soils (F.E. Clark, 1947). Fungi respond in a similar way, but less rapidly than bacteria. As to pathogenic fungi, their ability to cause root disease may increase in either wet or dry soils, depending on the moisture requirements of specific pathogens (cf. Ch. 19).

Very little is known on the effect of rain cycles, or irrigation, and the effects of long periods of drought, on the biological evolution of dryland soils.

Soil gases: Oxygen concentration and uptake by plants, and CO₂ production by roots may be critical for microbial activity, and cause changes in the pathogen and saprophytic populations, which can produce phytotoxic substances in the rhizosphere.

For example, in poorly aerated soils high in organic matter, and at high temperatures, ethylene produced by microbial activity and by the roots themselves, may cause an accumulation of ethylene in the rhizosphere. While low concentrations of ethylene may stimulate root growth, higher concentrations may have the opposite effect (Jackson et al., 1982).

A good soil structure permits sufficient air-filled pores that enable gas exchange with the atmosphere, and reduces the risk of anaerobic pockets developing.

Micro-organisms generally have greater specific rates of oxygen uptake than plant roots or seeds; therefore, if the supply of oxygen is restricted, competition for oxygen between plants and micro-organisms may occur (Lynch, 1983).

Soil pH: The activities of all microbial enzymes (about 1000 per cell) are dependent on the H⁺ ion, and are therefore influenced by soil pH (Lynch, 1983).

The pH of the soil near the roots tends to be more acid by one to two units than the bulk soil, due to the release of CO₂ and organic acids by the roots. These differences in pH have a significant influence on the activity of bacteria, actinomycetes, and some fungi in the rhizosphere.

The soil pH also influences species diversity (Lynch, 1983). The fungi can generally tolerate a wider range of pH, and some species, such as *Sclerotium rolfsii* can adjust pH to their own optimal values (Curl and Truelove, 1986).

Interactions between micro-organisms

Though the struggle for existence entails intense competition between the components of a mixed microbial population, and is particularly intense for micro-organisms sharing the same ecological niche, there are also interactions that are beneficial for one or both species involved. Interactions occur among the microflora and the microfauna, between the two, and even between strains of the same species.

Normally, microbial populations in the soil tend to maintain a biological balance; the greater the complexity of the biological community, the greater its stability (Baker and Cook, 1974).

Biological balance is of particular significance in host–pathogen relationships, and will be discussed in Ch. 19.

Growth-inhibiting relationships

There are three ways for micro-organisms to inhibit the growth of others: *competition* (mainly for nutrients); *antibiosis*, the production of metabolites that inhibit growth; and *parasitism* or *predation* (Curl and Truelove, 1986).

Antibiosis. Antibiosis may involve any inorganic inhibitor or organic toxin resulting from microbial metabolism (Alexander, 1977). The most common antibiotic-synthesizing micro-organisms are species of *Streptomyces*, *Bacillus*, *Pseudomonas*, *Penicillium*, *Trichoderma*, and *Aspergillus*.

Most antibiotics are chemically and biologically unstable, or may be adsorbed to soil colloids. Whilst they are extremely effective under specific conditions, the importance of antibiosis in the natural soil environment is still controversial (Curl and Truelove, 1986). Where considerable amounts of plant residues are present on or in the soil, as in stubble mulching, phytotoxicity has been observed; typical symptoms of cereal plants affected by phytotoxins include: reduced tillering, spindly stems, twisted leaves, yellowish leaves, shrivelled kernels, and small ears (Elliott et al., 1978).

Soil fungistasis is a situation encountered in practically all soils that prevents fungal propagules from germinating even when temperature and moisture are favourable; it is due to a combination of antibiosis and nutrient deficiency, both of which can result from microbial competition. Fungal propagules may lie dormant in the field soil, embedded in organic matter, until fungistasis is annulled by nutrients released from decomposing organic matter, microbial synthesis or root exudates.

Soil bacteriostasis inhibits bacterial development in nutrient-deficient soils. The phenomenon can be alleviated by air-drying the soil and can be eliminated completely by sterilization.

Garrett (1970) mentions the following attributes that confer a high competitive ability and can serve to appraise the ability of soil-borne pathogens to compete with soil saprophytes:

- rapid germination of propagules and rapid growth from a nutrient base;
- enzyme capacity for the decomposition of organic matter;
- production of fungistatic and bacteriostatic metabolites;
- tolerance to inhibitory substances produced by other micro-organisms.

Competition is not confined to saprophytes and pathogens; it can also impede the establishment of microbial associates in symbiosis with plants. *Rhizobium* spp. for example, are relatively weak competitors with the general rhizosphere flora. Once established within the plant tissues, from which the saprophytes are excluded, the symbionts are safe from further competition. The competition between *Rhizobium*

spp. and other micro-organisms in the rhizosphere has great practical significance in the cultivation of leguminous crops.

Parasitism and predation. In parasitism, the host is exploited and weakened without being destroyed; predation is the ultimate form of antagonism, since the host is destroyed. Though predators consume individuals, they rarely eradicate whole populations of the host on which their continued existence depends.

The most common parasites of bacteria are phages, which either live inside the host in a stable association or cause the dissolution of cell walls and protoplasm. Lysis is often associated with antibiosis. Bacteria are also parasitized by another bacterium believed to be widely distributed in soils: *Bdellovibrio* (Stolp, 1973).

Mycoparasitism, in which one fungus is parasitic upon another (Lumsden, 1981) comprises two groups: destructive parasites that kill the host, and balanced parasites that inflict little damage. Mycoparasites can attack a wide range of plant pathogenic fungi, but mainly soil-borne pathogens (cf. Ch. 19).

Certain fungal pathogens that serve as hosts to mycoparasites may in turn parasitize other fungi. For example, certain *Pythium* spp. can parasitize *Rhizoctonia solani*; the latter can parasitize several species of *Pythium* (Butler, 1957).

Predation involves interactions between microflora and microfauna, and between species of microfauna. Predacious fungi of the Hyphomycetes trap and consume nematodes, while Zygomycetes attack protozoa (Cook and Baker, 1983). Conversely, several genera of nematodes depend on fungi for food; others feed on bacteria and may serve as vectors of plant diseases. *Protozoa* feed mainly on bacteria; amoebae, mites and collembola are also mycophagous (Curl and Truelove, 1986).

Growth-promoting interactions

Commensalistic relationships. In commensalistic relationships, one organism receives benefits from another growing in close proximity, the latter not benefiting or being harmed in the process. At least four such relationships occur in the rhizosphere (Curl and Truelove, 1986):

- micro-organisms transform compounds and thereby release previously unavailable nutrients that are utilized by other micro-organisms;
- synthesis of a growth factor by one organism, that is essential for growth and reproduction of another organism; for example, a variety of growth factors as well as amino acids synthesized by one group of bacteria may be beneficial for other groups;
- changes in the physical environment by one organism may create a more favourable habitat for others; for example, *Streptomyces* spp. release ammonia during lysis of fungal mycelia, leading to a rise in pH;
- destruction of toxins by one organism may permit uninhibited growth for others (Fig. 10.4).

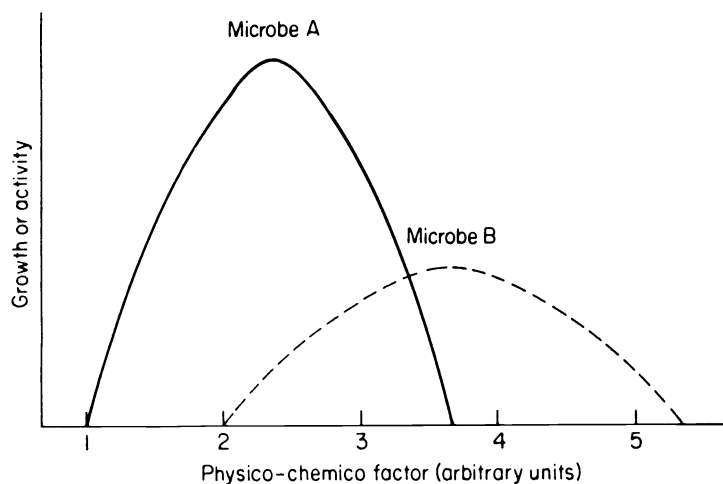


Fig. 10.4. Response of micro-organisms to factors in soil environment. As changes occur in the physical environment, resulting from activities of microbe A, conditions become unfavourable for A and increasingly favourable for B. From Lynch (1983). By permission of Blackwell Scientific Publications, Oxford.

Mutualistic relationships. In these relationships, the activities of different species of micro-organisms living in close proximity to each other, are mutually beneficial. A similar relationship between plants and micro-organisms is known as symbiosis.

The most common and well-known mutualistic microflora relationship is the alga–fungus association (lichen), which is primarily based on an exchange of metabolites between the two partners.

Soil micro-organisms in relation to plant nutrition

Certain groups of micro-organisms play extremely important roles in various processes – some favourable, some unfavourable – that have considerable bearing on soil fertility and plant nutrition.

Micro-organisms can affect plant growth in a number of ways (Curl and Truelove, 1986):

- nutrient availability and uptake;
- nitrogen fixation, symbiotic and nonsymbiotic;
- plant pathogen activity and disease.

The most important beneficial processes are described below; the effects on plant disease will be discussed in Ch. 19.

Decomposition of organic matter

The most obvious contribution of soil micro-organisms to plant nutrition is the decomposition of organic matter, resulting in the release or formation of ammonia, nitrates, sulphates, phosphates, etc.

Soil organic matter

The term 'organic matter' has a very broad meaning because it includes all materials of organic origin present in the soil, regardless of their origin or stage of decomposition. Thus, the term includes both fresh and highly decomposed crop residues and animal excretions, as well as the decomposing bodies of soil flora, fauna, and microbial components of the 'microcosm'.

Organic matter is not the same in all soils. The type of vegetation, the nature of the soil population, soil aeration and moisture conditions, climatic conditions, and management practices – all affect the kind and amount of source matter present in the soil. Soil organic matter is therefore truly a product of its environment.

Mineralization of organic matter

In a normal, productive soil, organic matter cannot accumulate. If the soil is not sterile, completely waterlogged, or excessively dry, every addition of organic matter will stimulate the activities of micro-organisms.

Many kinds of animals play an important initial role in the process by fragmenting the organic matter and making it available for soil micro-organisms.

Some residues, and specific constituents of complex residues, decompose more rapidly than others. Simple sugars, amino acids, organic acids, some proteins and many polysaccharides are completely utilized within a few hours to a few days (Behera and Wagner, 1974). Degradation of cellulose, some polysaccharides and chitin may continue for several weeks. The breakdown of the most resistant components, lignin, waxes and the dark, humic substances may require months to years (Haider et al., 1974).

Complete mineralization of organic matter does not occur; after the processes described above have taken place, and the original structure of the organic matter has disappeared, a dark brown to black residue, called humus remains. The gradual darkening of the soil increases its capacity to absorb heat and to warm rapidly in spring in continental climate dry regions (Smith and Elliott, 1990).

The soil humus generally decomposes at the rate of 2 to 5% annually in temperate climates, but far more rapidly in warm, semi-arid climates (Focht and Martin, 1979).

From 60 to 85% of the C in most fresh organic matter will be released as CO₂ within a few weeks to two to three months under favourable environmental conditions. Initially, about half the carbon consumed by the soil organisms will be utilized

for cell and product synthesis, to be released after death of the organisms (Focht and Martin, 1979).

Environmental factors

The activities of the micro-organisms involved in the various stages of this 'mineralization' of organic matter in the soil require certain essential environmental conditions: a favourable moisture régime, temperatures that are neither excessively high nor low, sufficient aeration, a balanced nutrient supply, etc. These requirements are identical to those needed for the normal development of most crop plants. Therefore, when conditions are favourable to crop plants, they are also favourable to the micro-organisms involved in the breakdown of organic matter. Under circumstances in which one or more essential requirements are in short supply, crop plants and micro-organisms may compete with each other for the limiting requirement – usually to the immediate detriment of the crop.

The level of organic matter in the soil, and the rate of its decomposition, are markedly dependent on temperature and soil moisture régime, which influence the development of the plants and the activities of the micro-organisms in the soil.

Jenny (1930) showed that every 10°C increase in the average temperature doubles the rate of decomposition of organic matter in soils when moisture conditions are favourable. The water supply affects the rate at which organic material is produced and also the rate of its decomposition, both increasing – up to a certain limit – with an improved soil moisture régime.

Optimum water potentials for the decomposition of organic matter in the soil are in the 0 to –15 bar range, but decomposition may continue until a water potential of –300 bar (Parr and Papendick, 1978).

The activity of the soil micro-organisms is influenced by the relation between soil temperature and soil moisture, the so-called 'hydrothermic quotient'. For example, in a sandy clay soil of a semi-arid region under natural veld, the optimum conditions for microbial activity were found to be a hydrothermic quotient in the range of 1.9 to 2.4, at a soil depth of 10–15 cm. This represented soil temperatures ranging from 20 to 30°C, and a soil moisture ranging from 11 to 14% (Pauli, 1967). Most soil organisms are incapable of activity at hydrothermic quotients below 1.5 or above 3.0 (*ibid.*), though there are some exceptions.

Semi-arid conditions are usually characterized by the alternation of a dry season and a rainy season, during which the combination of relatively high temperatures and a favourable moisture régime enables a considerable acceleration of the physical and biological factors that influence soil fertility. As a result, organic matter is rapidly mineralized (Pauli, 1967).

The major limitation to the activity of soil micro-organisms is the availability of carbon substrate, e.g. organic matter. The amount of organic matter in the upper layer of mineral soils usually varies from 1 to 10%, depending on climate, drainage

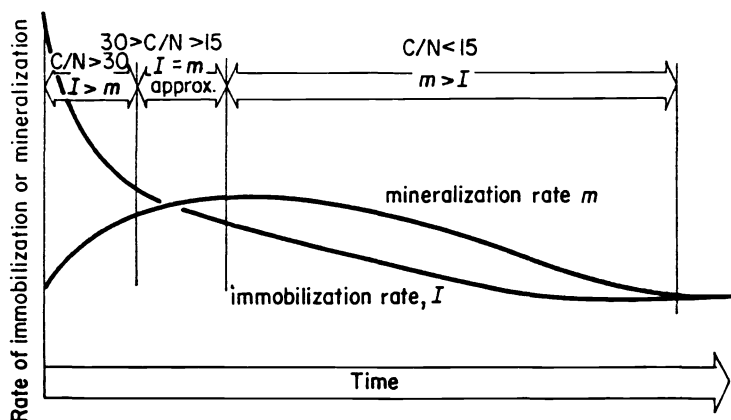


Fig. 10.5. Relationship between C : N ratios and N availability during the decomposition of plant residues. From Broadbent (1957). By courtesy of the US Department of Agriculture, Washington.

conditions, and farming practice. On an average, this organic matter contains 58% C; 5% N ($C/N=10-12$); 0.5% P, and 0.5% S (EUROCONSULT, 1989).

Carbohydrate–nitrogen balance

Most of the nitrogen in soils is tied up in organic matter, therefore carbon and nitrogen mineralization are linked together.

The main source of energy for soil micro-organisms consists of the carbohydrates of the organic matter; for the building of their body tissues they also require nitrogenous compounds. If these are not available in sufficient amounts in relation to the carbonaceous materials of the added organic matter, the micro-organisms will draw on the available sources of nitrogen in the soil. As far as the crop plants are concerned, this nitrogen is immobilized until the transformation of the organic matter into humus is completed and the micro-organisms themselves die and decompose. Organic matter with a C : N ratio of 20–30 will itself supply all the nitrogen required for its decomposition; with a ratio wider than 30, soil nitrogen will be immobilized, whilst with a ratio narrower than 20, nitrogen will be released at a fairly early stage of decomposition (Fig. 10.5).

This explains why the addition of undecomposed manure with a large proportion of straw, or the ploughing under of large quantities of cereal straw or stubble, with wide C : N ratios may cause a temporary deficiency of nitrogen, unless appreciable amounts of nitrogen fertilizers are added. Well decomposed manures, on the other hand, in which the nitrogen : carbon ratio has been narrowed during decomposition outside the soil, do not have this effect. Similarly, the ploughing under of an immature stand of leguminous plants will rapidly release nitrogen, which is immediately available to the crop following.

The decomposition of low-nitrogen organic matter requires a larger amount of

nitrogen in soils with high temperatures than in colder soils. A tonne of straw that is ploughed into the soil in winter, may require and 'fix' 8–9 kg of nitrogen, whilst the same quantity in summer may require 10–14 kg (Pinck et al., 1946). If other nutrients, besides nitrogen, are in short supply in the organic material to be decomposed, these may also be 'fixed' by the micro-organisms. The ratio of carbon to nitrogen in the top soil tends to be constant at approximately 10 : 1; in the subsoil the ratio is usually narrower, approaching 5 : 1. This may be due to fixed ammonium in the subsoil (Cooke, 1967).

Mineralization of nitrogen

The nitrogen bound in organic materials must be mineralized before it becomes available to plants.

Stages and rates of mineralization. To become available to plants, these organic compounds must first be mineralized. This mineralization occurs in three stages: aminization, ammonification, and nitrification. Each stage is the function of specific groups of micro-organisms, each group producing the substrate that is essential for the activity of the following group.

The rate of mineralization of the nitrogenous compounds may vary greatly, depending on the environmental factors affecting the activities of the micro-organisms involved in the process, and on the rate at which the nitrogen is taken up by the plants.

When crop production and, at the same time, the decomposition of the organic crop residues are limited by soil moisture, soil nitrogen is depleted relatively slowly. In the Great Plains of North America, the average loss in nitrogen over a period of 36 years was 39% in all (Hass et al., 1957).

The rate of mineralization of organic nitrogen in the soil increases from the air-dry condition to field capacity. The micro-organisms involved in nitrification continue to be active until near wilting point, whilst ammonification continues at even higher soil moisture tensions (Robinson, 1957). Consequently, water deficiencies will limit crop growth more than they will limit nitrification, and as a result plants grown under these conditions will generally have a higher nitrogen content than those grown under more moist conditions.

An opposite effect is obtained after the top soil has dried out and the plant draws most of its water supply from the subsoil, which is usually more deficient in nitrogen than is the top soil. Under these circumstances, nitrogen content of the plant tissues will be relatively more reduced by water deficiencies than will the yield of dry matter – unless the plant has taken up an excess of nitrogen before the top layer has dried out (Black, 1966).

Amounts released. In the course of the growing season of a crop, up to about 1–2% of the nitrogen may be released from the organic compounds present in the soil

(Black, 1968) if moisture is not limiting. This will supply up to 80–100 kg/ha N in fertile soils. The decomposition of the residues of the previous crop may supply another 10 kg/ha N. However, the micro-organisms that decompose the plant residues may require about double this latter amount of nitrogen for their own metabolic processes; this equivalent, therefore, becomes temporarily unavailable to the cultivated crop.

Release of other plant nutrients

Micro-organisms make a number of mineral nutrients available to plants through the decomposition of organic compounds, and oxidation or reduction of inorganic compounds in the soil. In semi-arid soils, up to 40% of the P, and 90% of the S are associated with the organic matter component (Smith and Elliott, 1990).

Ion uptake by plant roots can be stimulated by bacteria, probably by providing chelating agents or plant growth regulators that promote active ion transport. Under different conditions, bacteria can inhibit nutrient uptake, either by competition, or by producing phytotoxic compounds (Lynch, 1983).

The organic compounds containing P are derived from the decay of animal and plant bodies. P uptake by plants is always greater in non-sterilized soil than in sterilized soil, indicating the importance of micro-organisms in phosphorus nutrition (Alexander, 1977). Phosphorus is readily incorporated by bacteria into nucleic acids (Lynch, 1983).

Maintenance of soil organic matter

Rate of loss under cultivation

The amount of organic matter in the soils of arid regions is extremely low, being frequently limited to mere traces and rarely exceeding 1% (Lemée, 1955), for the following reasons:

- the sparse plant cover produces very little in the way of residues;
- the dried residues are dispersed by the wind;
- the rapid mineralization of the organic matter;
- the small contribution of animal manure; and
- the use of most of the organic residues for fuel.

The mineralization of the meagre amounts of soil organic matter in the Sahelian zone of West Africa during the cropping season amounts to 4–5% per year (Smith and Elliott, 1990).

By contrast, soils in the semi-arid regions with continental summer rainfall, which were originally grass prairies, were able to build up relatively high levels of organic matter; after they were brought under cultivation, they were able to release readily decomposable soil organic matter which provided an adequate supply of plant nutri-

ents for many years. However, the rapid rate of decomposition in cultivated semi-arid soils, largely the result of high temperatures, where rainfall occurs during the summer (Focht and Martin, 1979), led to a rapid depletion of these reserves. Soil organic matter mineralization in the steppe semi-arid regions occurs at a rate of about 2% annually (Smith and Elliott, 1990).

Overall, reductions in soil organic matter over time in agricultural soils are largely due to tillage, inadequate residue return, and soil erosion. Carbon loss through tillage is mainly due to accelerated oxidation of the organic matter. The equilibrium level of soil organic matter is determined by the interaction of many factors, including precipitation, temperature, soil type, tillage, cropping system, and crop residues (Smith and Elliott, 1990).

Importance of soil organic matter

The organic matter content of the soil is highly correlated with its potential productivity, tilth and fertility. Although the amounts of soil organic matter in most semi-arid dryland soils is relatively low (generally less than 1%), it has a major impact on soil fertility (Smith and Elliot, 1990). It is the vital component in the dynamic equilibrium between soil degradation processes and soil conservation practices. Hence the need to replenish and maintain the level of organic matter through regular additions of organic materials (Parr et al., 1990).

Beneficial effects. The favourable influence of organic matter, in the form of crop residues, manure, or composts, on soil fertility, is due to the following effects:

(1) During and after decomposition, essential plant nutrients, such as nitrogen, phosphorus, potassium, and micro-elements, are gradually released. Organic matter is therefore an important store of plant nutrients.

(2) The humic compounds formed during the decomposition of organic matter may prevent the formation of certain mineral-phosphate complexes in which the phosphorus is unavailable to plants. They may even reverse the process, by forming a soluble and available phosphate complex. The humic compounds may also increase the availability of many micro-elements (Pauli, 1967).

(3) The colloids formed during decomposition are active in the cation exchange complex (CEC) of the soil. In sandy soils, the exchange capacity is almost entirely due to organic matter.

(4) The decomposition of organic matter improves soil structure – both directly, by providing sticky substances that are needed for aggregation of soil particles, and indirectly, by increasing the water-holding capacity of the soil, improving aeration, facilitating tillage operations, and reducing erosion hazards.

By improving the moisture régime of the soil, water-deficit stress situations are less likely to occur in soils rich in organic matter.

Palti (1981) stresses that one cannot separate the beneficial effect of organic matter

on the soil moisture régime from its biological effects, such as its influence on micro-biota and their relation to plant pathogens.

(5) Organic matter serves as a source of energy and food for the many groups of micro-organisms involved in biological processes that are of significance to soil fertility.

(6) The decomposition of organic matter in the soil releases considerable amounts of carbon dioxide, of which a large proportion escapes into the air. As the carbon dioxide is heavier than air, it concentrates in the atmosphere above the soil, and can be taken up by the leaves of plants during the day and assimilated in photosynthesis. Manuring the soil therefore increases the nutrient-engendering content of the atmosphere!

It accordingly follows that all the beneficial effects obtained from the addition of organic manures to the soil, are dependent on their decomposition under favourable conditions.

There is no point in attempting to increase the organic-matter content of the soil, as an objective in itself; but there is need for a regular supply of organic matter at a level that is commensurate with the rate of its biological decomposition.

The chernozem soils are often considered to be highly fertile, and yet crop yields on them are frequently disappointing. This is mainly because the decomposition of the high proportion of organic matter present in these soils is limited by the heat and drought of the late summer and the extreme cold of winter (Crowther, 1947).

However, not all decomposition of organic matter has favourable effects: whilst the decomposition of organic matter under aerobic conditions produces nitrates, sulphates, phosphorus, and compounds of calcium, magnesium, potassium, iron, etc., the dominant products of decomposition under anaerobic conditions are methane, hydrogen sulphide, ammonia, aldehydes, and ferrous iron (Vershinin et al., 1959).

Sources of organic matter

Wherever possible, an adequate level of soil fertility should be maintained by returning crop residues, using manures, composts, green manures, and the inclusion of forage legumes in the crop rotation.

Crop residues. Crop residues fulfil an important role in dryland agriculture. The areas involved are too extensive and/or too remote to be supplied with organic manures or organic wastes; crop residues are, under these conditions, the only potential source of organic matter. Crop residues also act as mechanical barriers reducing soil erosion by wind and water.

After a few years of increased fertilizer use and crop residue management, the nutrients released from humus and residual carry-over from fertilizers will generally suffice to offset the nitrogen requirements of the micro-organisms and avoid competition for nitrogen with the crop (Tisdale and Nelson, 1975).

Unfortunately, in commercial agriculture, there is a tendency to view crop residues as a nuisance. They interfere with tillage operations and harbour rodents, insects, pathogens, weed seeds; hence the general tendency to solve these problems by burning the residues.

Lynch (1983), in reviewing the results of long-term (83 years) experiments in Denmark, concludes that "the input of organic matter from manure to the overall soil organic matter is small by comparison with the input from plants". If this is true for a temperate climate, it is probably still more significant for rain-fed farming in semi-arid regions, and above all for irrigated agriculture, characterized by the rapid turnover of organic matter in the soil.

In subsistence agriculture, yields are generally low, and contribute little organic matter to the soil, and crop residues are generally removed from the field to serve as forage or fuel. Whatever remains is rapidly decomposed because of the warm climate and long growing season. Where residues are left on the soil surface, their complete elimination in a short time by termite activity occurs in many places (El-Swaify et al., 1984). Consequently, the soils in these regions are generally poor in organic matter, have poor physical structure, and erode easily.

Even small amounts of organic matter in the soil can be significantly beneficial to nutrient status, ion retention capacities and stable soil structure in relatively inert soils (ibid.), hence the importance of an adequate and regular supply of organic matter (OM) to the soil.

The first important practice for maintaining an acceptable level of OM in the soil is to return crop residues to the soil. Continued removal or burning of the residues inevitably results in decreases in soil productivity; however, even when all residues are returned to the soil, nutrients are exported with the crop, and/or lost by leaching, volatilization of N, and erosion. Therefore, in order to maintain productivity, farmyard manure and/or fertilizers need to be added to the land in appropriate quantities.

The decomposition of crop residues by soil micro-organisms requires some nitrogen, which will be tied up for a time, possibly competing with young plants for nitrogen in short supply (cf. p. 476). An estimated 1 kg of N is used by micro-organisms in converting 100 kg of crop residues to humus (Dryland Agriculture Technical Committee, 1979). Most cereal straws have C : N ratios ranging from 80–120 : 1; their decomposition will therefore result in immobilization of N (Smith and Elliott, 1990).

Modern management techniques (conservation tillage) are based on the conservation and recycling of crop residues and the techniques for coping with the problems outlined above have been developed and are described in Ch. 14.

Animal wastes. Mathan et al. (1978) found that even with continuous cropping of a black soil in India, farmyard manure and crop residues increased the organic carbon and nitrogen by 20 to 40% in three years.

A large proportion of the nutrients contained in animal manures is frequently lost

as a result of run-off, volatilization and leaching during storage and poor hauling and inefficient spreading practices. Measures that can reduce these losses are frequently economically costly to apply (NRC, 1989).

Composting has the advantage of increasing the nutrient concentration of animal manures and reducing the volume of the material to be applied; it is, however, little used (Granatstein, 1988).

In order to develop more efficient systems for storage and handling of animal wastes, “research is needed to devise low-cost systems of producing biogas from animal manures, make efficient application methods more economical, and educate farmers about the beneficial aspects of manure” (NRC, 1989).

A rough estimate of the total plant, human and animal wastes available in developing countries indicates that if these were used as organic manures, they could supply about 100 million ton of nutrients (consisting of 47% N, 38% K and 15% P), equivalent to eight times the total fertilizer consumption of these countries in 1970–1971 (FAO, 1977). However, there are enormous difficulties involved in mobilizing and using these wastes. Much of the animal husbandry in developing countries, for example, is completely separate from arable cropping, and cannot therefore be used as a source of manure for the latter. Much of the dung is also used as fuel and is lost as a source for plant nutrients. Even if every effort is made to collect organic wastes and use them efficiently, the use of the fertilizers to make up the shortfall will remain indispensable.

Green manures. The energy costs of sowing legumes for green manure are relatively low; however, this requires land, and without phosphoric and/or potassic fertilizers, the production of organic matter is likely to be low.

It should also be mentioned that green manures have given very inconsistent results; in particular, in tropical soils their effect has often been insignificant (Meiklejohn, 1955).

A green manure crop widely used in the rice paddies in China and Vietnam is a water fern-azolla, which in symbiosis with blue-green algae *Anabaena* lives on the surface of flooded paddy and fixes atmospheric nitrogen.

The limitations of green manures are discussed in more detail in Ch. 16.

The soil rhizosphere

Description and importance (Fig. 10.6)

Plant roots provide a major source of energy for the soil micro-organisms, and the term rhizosphere refers to the volume of soil in which microbial numbers and activity are influenced by the proximity of a root (Fitter and Hay, 1981).

The stimulation of bacterial activity in the rhizosphere is due to:

- the sloughing off of root hairs and caps as the root grows;

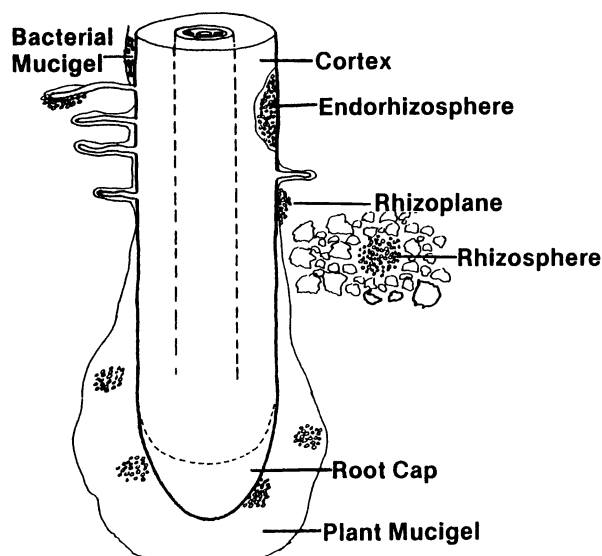


Fig. 10.6. Schematic illustration of the distribution of micro-organisms in the root zone. From Giddens and Todd (1984). By permission of the Soil Science Society of America, Inc., the American Society of Agronomy, Inc., and the Crop Science Society of America, Inc.

- the exudation of a considerable range of compounds from root cells;
- the production of mucigel by the root cap.

The mucilage which covers root surfaces, and in particular in apical zones, is a gelatinous material consisting mainly of polysaccharides and polygalacturonic acids. In soil-grown plants the mucilage is generally invaded by micro-organisms; the mixture of mucilage, micro-organisms and soil particles is called mucigel (Oades, 1978).

A variety of functions are ascribed to mucigel: (a) a role in nutrient absorption; (b) the protection of the apical region of the root from desiccation and of the root tips from injurious substances; and (c) the mucigel acts as a lubricant, improving soil–root contact, especially in dry soils (Curl and Truelove, 1986). In dry soils, more mucilage is released in response to mechanical impedance (Oades, 1978).

Nutrient absorption in the rhizosphere may result in differential ion uptake. The rapid absorption of phosphorus by roots may lead to a local depletion of available P in the rhizosphere if the rate of diffusion of P is slower than uptake. Conversely, certain ions, such as Ca and Al, may be absorbed very slowly, leading to their accumulation in the rhizosphere. The carrier used in N fertilizers may affect the pH of the rhizosphere (Bowen, 1981). Besides the direct effects on the plants, these changes may bring about changes in the rhizoplane microflora (Smiley, 1975).

Plant–micro-organisms interactions

In the aggregate, the amount of energy made available to the inhabitants of the

rhizosphere can be quite considerable; Martin (1977) has estimated that over a period of 23 days, nearly 40% of the carbon transported to the roots of wheat was lost to the soil.

As a result of the favourable conditions encountered in the rhizosphere, the population density of soil micro-organisms there may be several times higher than in the bulk soil; the usual interactions between plants and soil micro-organisms are also considerably stimulated. These interactions are symbiotic, competitive or parasitic.

There is, however, no clear-cut distinction between symbiotic associations and parasitic associations. Fitter and Hay (1981) propose the flow of metabolites as a useful indicator: the flow is reciprocal in symbiotic relations, and one-way in the other cases.

Symbiotic: such as dinitrogen fixation; stimulation of nutrient uptake; release of ions from organic matter and improved availability of insoluble elements.

Non-infecting micro-organisms promote the mineral nutrition of plants through their influence on (a) the growth and morphology of roots; (b) the physiology and development of plants; (c) the availability of nutrients; and (d) nutrient uptake processes (Rovira et al., 1983).

Symbiotic associations, such as those with N_2 -fixing bacteria or mycorrhiza, are rarely obligate, and plants can survive without them; they do however enable plants to obtain N and P, respectively, from soils deficient in these elements, and thereby to extend the range of suitable habitats. Fitter and Hay (1981) stress that a price has to be paid by the host plant in the form of an adequate supply of synthates to the associated organisms. The implications of this 'biological tax' will be discussed for dinitrogen fixation, and the implications for plant/mycorrhiza associations are probably similar.

Competitive: such as competition for phosphorus and nitrogen between roots and microbes; or interference with nutrient uptake, as in the case of release of phenolic acid resulting from the breakdown of lignin by many fungi (Pareek and Gaur, 1973).

Parasitic: damaging roots and plants. The pathogenic fungi will be dealt with in Ch. 19.

Dinitrogen fixation

Dinitrogen fixation is the assimilation of free N_2 from the air by soil organisms, and the formation of N compounds that eventually become available to plants.

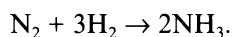
It has been estimated that the annual contribution of dinitrogen fixation to agricultural production worldwide, probably exceeds four- to fivefold all the N fertilizers produced by the fertilizer industry in a given year (Brill, 1977).

The increase in world demand for N fertilizers and the steep increase in the cost of energy have stimulated interest in biological N_2 fixation.

Biochemistry of N₂ fixation

Molecular N cannot be directly used by plants; first it has to be combined with other elements – a reaction which requires very large expenditures of energy. The required energy can be supplied in nature by lightning; its main source however, is the activity of various groups of micro-organisms.

The process whereby N in its molecular form in the atmosphere is fixed and converted to an organic form is termed dinitrogen fixation. The reaction involved is:



There are three major biological N₂-fixing systems: symbiotic, associative, and free-living.

Distinct differences exist between the three systems as regards energy source and fixation capability; however, all N₂ micro-organisms have the same high energy requirements and the principal steps in the fixation process are the same. Furthermore, whether N₂ is fixed biologically or by an industrial process, the product, ammonia, is identical and equally effective as a plant nutrient.

In essence, the fixation process consists of the reduction of N₂ to 2NH₃; this reaction is catalyzed by nitrogenase (an enzyme complex that is unique to N₂-fixing micro-organisms) in combination with the necessary reactants (Marschner, 1986).

The nitrogenase reaction is severely inhibited by O₂, and the enzyme is even destroyed at high O₂ concentrations. On the other hand, there is a large demand for energy in the form of ATP, which is produced mainly during respiration (Evans and Barber, 1977). N₂-fixing micro-organisms overcome these conflicting demands in a number of ways (Marschner, 1986):

- by living under anaerobic conditions (e.g. *Clostridium*);
- by consuming most of the O₂ by excessive respiration (e.g. *Azotobacter*);
- by regulating O₂ transport enzymatically by leghaemoglobin from outside the nodules to the bacteroids, an exceedingly low O₂ concentration is maintained on the bacteroid surface.

Biological N₂-fixing systems

The capacity for biological N₂ fixation is restricted to some species in 11 bacterial families, and some species in 8 cyanophyceae (blue-green algae) families (Werner, 1980).

Symbiotic systems

Symbiotic systems generally have the highest fixation capability because the supply of carbohydrates as an energy source to the micro-organisms comes directly from the host plants.

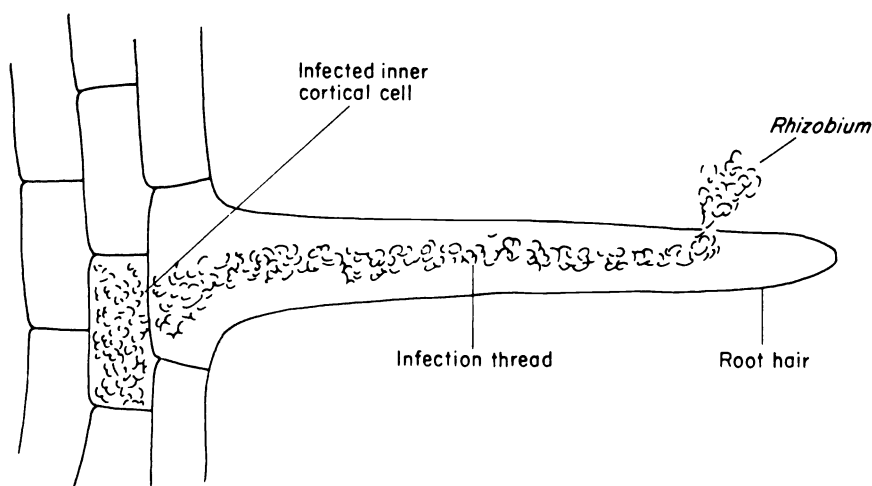


Fig. 10.7. Infection of a root hair by *Rhizobium*. The infected inner cortical cell swells and divides to initiate the nodule. From Lynch (1983). By permission of Blackwell Scientific Publications, Oxford.

Nodulated legumes. The fact that certain crops, such as vetches, clovers and lucerne are capable of improving soil fertility, was already known in ancient times. In 1892, M.W. Beijerinck identified the specific organism which was capable of fixing atmospheric nitrogen in symbiosis with a legume plant as a bacterium belonging to the genus *Rhizobium*.

Of the three subfamilies of leguminosae: caesalpinioideae, mimosoideae, and papilionoideae, only the two latter are relevant in this context. The mimosoideae include *Acacia*, *Leucaena* and other trees and shrubs, as well as some annual forms. The plants are often very well adapted to arid areas, and nodulation is a general attribute (Sprent, 1985). Normally, fixation is limited to wet periods (Langkamp et al., 1982).

The papilionoideae include a few trees, but comprise nearly all the legumes grown for grain or forage production. On the whole, they are not very drought-tolerant, but there is scope for breeding more drought-tolerant lines (Sprent, 1985).

Plant-rhizobium relationships. The rod-shaped bacteria are mobile in the soil; their mobility is however dependent on an adequate supply of available phosphorus.

The roots of legumes excrete tryptophane, which is converted by *Rhizobium* bacteria into indole acetic acid (IAA), a growth substance that promotes enzyme degradation of root cell walls. Root-hair curling and infection thread formation then follow.

The thread then penetrates the root cortex and induces the formation of meristems. The bacteria multiply rapidly and cause the formation of a typical swelling of the root: the root nodule (Fig. 10.7).

During nodule growth, the bacteria are transformed into bacteroids, which are

much larger than the original bacteria. This transformation is closely related to the synthesis of haemoglobin, nitrogenase and other enzymes whose role in N_2 fixation was mentioned above. After their change into bacteroids, the bacteria no longer multiply, so that all substrate energy can be diverted to N_2 fixation (Lynch, 1983).

After infection, it generally takes three to five weeks before the N_2 -fixation process begins; during this period, carbohydrates, mineral nutrients and amino acids are supplied by the host plant without any benefit; the relationship of the bacteria to the host plant during this stage is therefore entirely parasitic. Because the plants must rely on a supply of combined nitrogen during this period until a leaf area is developed that is large enough to supply the combined demand of host plant and growing nodules, it is often recommended to farmers to apply an early dressing of N fertilizer during this critical period. However, the presence of easily available nitrogen will retard infection and proliferation of the *Rhizobium* and will generally achieve the opposite of the desired effect.

Once the N_2 -fixation process is initiated, the relation between bacteria and host plant becomes typically symbiotic.

The bacteria obtain some of their nutritional requirements from the host plant which delivers sucrose via the phloem to the nodules as a substrate from which the energy required for N_2 fixation is derived. The oxidation of the sucrose produces ATP and reductants, and there is a considerable release of respiratory CO_2 .

The N_2 -fixation product, NH_3 , is released into the plant cytosol, where it is synthesized into amides, amino acids, and ureides. These nitrogenous substances are absorbed into the root xylem, and then partly transported to the shoots, and partly excreted into the soil, where they may benefit non-leguminous plants growing in association with the legume.

High concentrations of NH_3 , glutamine, and glutamate inhibit nitrogenase and repress the N_2 -fixing process. This has significant implications regarding the application of N fertilizers to legumes.

Closely related to the N_2 -fixing capacity of the root nodules, is the presence of leghaemoglobin, a red-coloured enzyme (Werner et al., 1981). Leghaemoglobin controls oxygen diffusion so as to maintain micro-aerobic conditions for N_2 fixation (Lynch, 1983). Cobalt is essential for the synthesis of leghaemoglobin, and its function is probably related to the involvement of vitamin B12 in the synthesis of leghaemoglobin (Marschner, 1986).

In annual grain legumes, and to a lesser extent in pasture legumes, the maximum rate of N_2 fixation is reached at the onset of flowering and then declines rapidly, as sink competition for photosynthates and nodules intensifies between the developing seeds and the nodules (Haystead and Sprent, 1981). Lawn and Brun (1974) have shown that soybean nodules senesce during the early and critical pod-filling period.

Though the relationship described above is typically of mutual benefit to host plant and bacterium, there are circumstances when this symbiosis is no longer maintained. Whenever conditions occur which limit or arrest N_2 fixation by the nodule

bacteria, the relationship with the host plant ceases to be symbiotic, and becomes typically parasitic; the bacteria continue to obtain their nutrient supply from the host plant, without the latter benefitting in any way from the presence of the nodule bacteria.

Requirements for effective nodulation:

(1) *Environmental.* During the infection stage, the process is very sensitive to unfavourable soil conditions, such as salinity, calcium deficiency, low soil pH, and many other factors of the soil environment that affect the host plant (Munns, 1978).

Environmental conditions that favour growth of the legume also favour active and effective nodulation of the host plant. These conditions are: high radiation, optimal temperatures, adequate soil moisture and aeration, suitable soil pH, and a balanced supply of soil nutrients (Smartt, 1976).

Carbohydrate supply to the root nodules is adversely affected by low light intensities; after several days of low light, the rate of dinitrogen fixation decreases, and an increasing proportion of the red, active nodules change into green, non-fixing types (Haystead and Sprent, 1981).

High soil temperatures adversely affect nodule fixation. In Australia, the nodules of subterranean clover were found to fix N_2 actively at 20°C, with an optimum at 25°C, and almost complete cessation at 30°C (Meyer and Anderson, 1959).

Of particular significance for dryland agriculture is that adequate moisture is the first essential for the symbiotic relationship between the host plant and *Rhizobium*. Water stress reduces seedling nodulation (Heichel, 1987), and nitrogenase activity was reduced 85% compared with controls at a leaf water potential of -15 to -20 bar (Aparicio-Tejo et al., 1980). When the moisture deficit in the crop becomes severe, the host sheds its nodules (E.W. Russell, 1973).

In dry soils, nodules may lose water more rapidly than the vascular system can maintain supply; nodules vary in their general structure and therefore also differ in their resistance to moisture stress. Many nodules produce suberized lignified layers at or near the surface, which act as diffusion barriers limiting both water loss and oxygen uptake (Sprent, 1985).

On plants such as *Prosopis*, with deep roots, the nodules form deep in the soil, where they suffer less from heat and desiccation (ibid).

Drought affects N_2 fixation in several ways. In the short term, oxygen diffusion may be a constraint which is subsequently supplemented by reduced supplies of photosynthates to the roots (Sprent, 1985).

Hume (1978) found that irrigation increased N_2 fixation in peanuts and soybeans. Rainfall may leach out much of the fixed nitrogen before the following crop can benefit from it.

Rhizobia are sensitive to certain concentrations of fungicides, insecticides and herbicides in the soil (Curl and Truelove, 1986).

(2) *Nutritional.* Curl and Truelove (1986) cite convincing evidence that the application of mineral fertilizers generally increases microbial populations in the rhizo-

sphere, although there are studies in which fertilizers were found to have no influence.

Of the mineral nutrients, combined nitrogen has the most profound effect on N_2 fixation in legumes; its influence can be either stimulating or depressing, depending on the amount of N available. High levels of soil or fertilizer N can inhibit root infection by the *Rhizobium*; during growth of the crop they cause a marked decline in N_2 fixation and a shift from symbiotic to inorganic N nutrition (Carroll and Greshoff, 1983).

An inadequate supply of P has a greater adverse effect on nodulation and nodule growth than the direct effect on growth of the host plant. However, because of the low level of N_2 fixation, resulting from P deficiency, the host plants show N deficiency symptoms which can be relieved by the application of P fertilizer.

The bacteria also require an adequate supply of calcium. Insufficient available molybdenum causes N-deficiency symptoms. Cobalt deficiency impairs the synthesis of leghaemoglobin and therefore results in low nodule activity. The transport of sugars to the nodules breaks down if boron is deficient (Carroll and Greshoff, 1983).

Enemies. The *Rhizobium* bacteria, in their free-living stage, are subject to attack by various types of fungi, by bacteria of other groups, and by bacteriophages. They are generally able to hold their own, but unfavourable environmental conditions can easily upset this balance, with disastrous results for the *Rhizobium* and their host plants. It is surprising that, notwithstanding the large number of factors which can affect the relationship between host plant and bacteria, symbiosis is the rule and parasitism the exception.

Genetic variability. The nodule bacteria are all of the genus *Rhizobium* but belong to a number of groups of strains, each of which infect certain host plants or groups of plants. In each group of bacterial strains are found individual ones that differ in the efficiency with which they fix nitrogen. The inefficient strains form very small nodules, few in number, which degenerate rapidly.

The efficiency of nitrogen fixation also depends on the host plant and its ability to 'cooperate' with the bacteria; this ability is a hereditary trait.

There exists, therefore, the entire spectrum of relationships between host plant and bacteria, ranging from absolute parasitism to full symbiosis.

As in all bacteria, mutations may occur in *Rhizobium*, changing efficient strains into parasitic strains. Selected strains for inoculation should, therefore, in addition to being efficient in nitrogen fixation, also show great genetic stability and aggressiveness in competition with native strains.

Inoculation. Different *Rhizobium* species have various degrees of host specificity or host preference. Therefore, if legumes are grown on soils in which the appropriate *Rhizobium* species is not present, inoculation with a suitable species is essential for effective nodulation. Within species, there are considerable differences in the efficiency of N_2 fixation, and inoculants are generally made with selected, highly efficient strains.

Evans et al. (1979) found that a bacteriophage reduced the population of a susceptible strain of *Rhizobium trifolii* in the rhizosphere of clover, which was replaced by variant substrains resistant to the phage, but less effective in symbiotic N₂ fixation. The authors conclude that phages may have a role in determining the relative nodulating efficiency of selected *Rhizobium* strains.

Some inoculant companies sell *Rhizobia* mixed with molybdenum salts to ensure that N₂ fixation should not be prevented by Mo deficiency.

Inoculated seed should be sown into a moist seedbed, otherwise the inoculant may become ineffective if the seed remains for a longer time in dry soil.

Amounts of dinitrogen fixed. The total amounts of dinitrogen fixed by *Rhizobia* may be quite considerable, and range from 50 kg/(ha year) for subterranean clover in New South Wales (Donald and Williams, 1954) to 250 kg/(ha year) for lucerne in Arizona (Smith, 1944). An indirect indication of the level of nitrogen provided to the plant is given by the following example:

In a trial with peanuts grown for the first time in a loess soil in the Negev, in which specific symbiotic bacteria were entirely lacking, inoculated seed produced the same yield without nitrogenous fertilizers as non-inoculated seed grown with nitrogenous fertilizer (Shiffman, 1961). It can therefore be assumed that the *Rhizobia* fixed at least the equivalent of the amount of nitrogen applied in the fertilizer, namely, 180 kg N per hectare (Fig. 10.8).

The amounts of nitrogen fixed in the host plant are no indication of the amount of residual nitrogen that may remain available to the following crop.

This latter amount depends primarily on the conditions under which the host crop was grown, on the stage at which it was harvested, and on the conditions prevailing during the period between harvesting the legume and the following crop. Legumes harvested for seed will leave very little or no residual nitrogen behind in the soil.

Nodulated non-legumes. Many non-leguminous plants, in particular some that are indigenous to desert areas, (e.g. *Opuntia* and *Artemisia*), fix N₂ through symbiosis with a variety of organisms. Focht and Martin (1979) report that planting *Alnus* on crop lands is practised in some parts of Africa as a means of N supply to the soil. The endophyte associated with *Alnus* is an actinomycete that is very resistant to desiccation.

Some of the desert non-leguminous N₂ fixing plants, can fix as much N₂ as the legume-*Rhizobia* association, and it is thought possible that they may be at least partly responsible for the high concentration of nitrates occasionally found in groundwaters (Focht and Martin, 1979).

Various genera of dicotyledonous plants form root nodules with a filamentous actinomycete *Frankia*. The only genus that grows well in hot dry, and saline environments is *Casuarina*, which not only fixes appreciable amounts of dinitrogen, but also provides shade and fuel wood (Sprent, 1985).

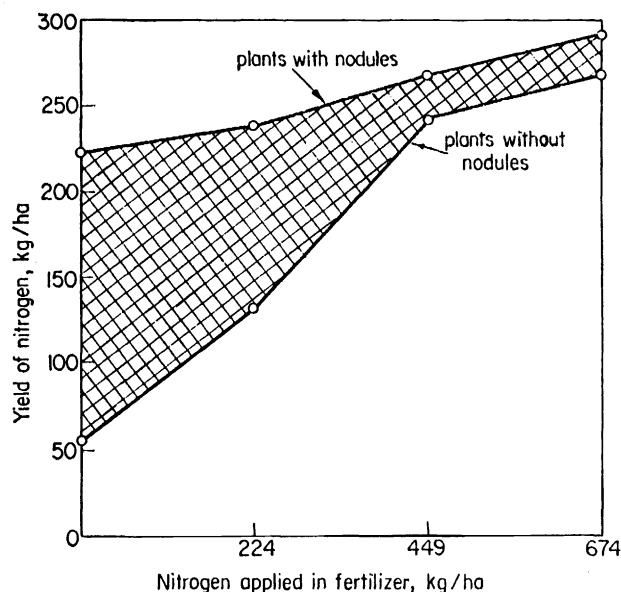


Fig. 10.8. Yield of nitrogen in above-ground portions of nodulated and non-nodulated soybeans. The plants were grown on soil treated with ground maize to immobilize the nitrogen. The shaded area represents the difference in N uptake due to nodulation. From Weber (1966). By permission of the American Society of Agronomy, Inc.

Associative systems

Some N_2 -fixing systems with a high host specificity do not develop nodules but inhabit the root surface or intercellular spaces of the cortex cells. These are called *rhizosphere associations* (Döbereiner, 1983).

In certain grasses the N_2 -fixation capability of these associations is very high. *Azospirillum* has been shown to stimulate growth of wheat (Avivi and Feldman, 1982) and of millet (*Setaria italica*) (Yahalom et al., 1984) when supplied with both small and large quantities of N fertilizers.

The association of bacteria with C4 grasses and cereals is probably the potentially most important N_2 -fixing system in an arid environment, because of the high water use efficiency of these grasses. They include *Digitaria decumbens*, *Brachiaria decumbens* and many others, as well as maize, sorghum and other cereals. The associated bacterium is *Azospirillum lipoferum* (Sprent, 1985). In the association between *Paspalum notatum* and the bacteria *Azotobacter paspali*, the bacteria live in the mucilage layer outside the plant roots and use root exudates as a source of nutrients (Mengel and Kirkby, 1982).

Inoculation with *Azospirillum* has not improved yields consistently (Klingmuller, 1983).

Free-living systems

Requirements for the functioning of free-living, N_2 -fixing bacteria include: the availability of C compounds; adequate inorganic nutrients; optimal pH for growth; and low oxygen tension (Mulder, 1975). The product of the fixation is ammonia, which is then incorporated into amino acids and proteins.

Free-living micro-organisms in the soil or on the soil surface are generally limited in their N_2 fixation ability by an insufficient amount of organic matter in the soil, for which they have to compete with carbon-heterotrophic micro-organisms. They are also less efficient in fixing dinitrogen than the symbiotic bacteria (Mulder, 1975). The annual amount of fixed N_2 is generally about 1 kg/ha (Bothe et al., 1983).

Amongst the groups of micro-organisms that are capable of fixing N_2 from the air independently are *Azotobacter*, *Beijerinckia*, *Clostridium* and several species of algae. *Azotobacter* is more common in neutral or alkaline soils, and *Beijerinckia* in tropical soils. Both micro-organisms have the same optimal growth temperature, but *Azotobacter* is inhibited by the low P and high Al contents characteristic of many tropical soils (Focht and Martin, 1979).

All species of *Azotobacter* fix N_2 and do this at a faster rate and greater efficiency than any other bacterium using N_2 as its sole N source (Mulder, 1975). An advantage of *Azotobacter* in drylands is that it can form cysts, which resist desiccation.

The first attempts at increasing N_2 fixation by inoculating cereal seeds with *Azotobacter* were made in the former USSR (Mishustin, 1970). The positive results reported in the literature encouraged follow-up experimentation in the 1960's in a number of countries, including Australia, India, and Britain; the results were conflicting and were evenly divided between positive, neutral, and negative (Lynch, 1983).

Several companies, in different countries, are marketing *Azotobacter* inoculants.

Scherer et al. (1984) have shown that *Nostoc flagelliforme* from hot, dry areas in China can survive two years of drought; on rewetting it takes up water very rapidly. Although the amounts of dinitrogen fixed by cyanobacteria are relatively small, in a water-limited environment they might make a significant contribution (Sprent, 1985).

Blue-green algae (cyanophyceae), now known as cyanobacteria, are free-living organisms at the soil surface or in shallow water. They are capable of adding appreciable amounts of nitrogen to dry-region soils if there is an abundant supply of water and sunlight on the soil surface (Lynch, 1983). After irrigation, an algal layer appears on the soil surface, that remains active in N_2 fixation after the soil dries.

The association of a floating fern *Azolla pinnata* with a blue-green alga *Anabaena azollae* can play an important role in N fertilization of paddy rice fields. The annual N_2 fixation rates of blue-green algae are estimated as 30–50 kg/ha N, as long as the availability of combined N is maintained at a low level (Sen Gupta et al., 1982). Other authors even reach higher estimates: Bothe et al. (1983) indicate that the atmospheric nitrogen fixed during a season of flooded rice has been found to amount to 50–80 kg/ha (Bothe et al., 1983).

Lichens fix dinitrogen only when they contain a cyanobacterial component; however, such a component is not always present (Sprent, 1985).

Dinitrogen fixation – an overview

Considerable optimism has been expressed on the potential benefits of the greater use of N_2 fixation by micro-organisms. Major areas for research on root nodules in legumes are: effective symbiosis for new grain and forage legumes; ability to compete with inferior strains; tolerance of environmental stresses (Abbott et al., 1988); increasing the efficiency of the process. For non-legumes: inducing a similar symbiotic relationship by transferring the N_2 fixing *nif* genes to the plants directly or through a microbe-plant association (Lynch, 1983).

Limitations

It is generally not appreciated that biological N_2 fixation is very energy demanding.

The bacterial process of dinitrogen fixation from the air requires approximately the same amount of energy per unit of fixed nitrogen produced ($\pm 15\,000$ kcal/kg) as the chemical manufacturing processes (Revelle, 1976). In the symbiotic processes, the energy required is supplied by the photosynthates produced by the host plant, and therefore competes with other physiological activities in the plant for the products of photosynthesis.

About one-third of the total carbon fixed by photosynthesis is moved to the nodules and less than half of this is returned to the aerial portions of the plant (Hardy and Havelka, 1975).

For every ton of soybeans, with a protein content of 30 to 40%, 100 kg of nitrogen must be fixed, consuming energy from 400 kg of carbohydrates. By comparison, the natural gas and naphtha commonly used in industrial nitrogen fixation have a high energy content, and consumed only $1\frac{1}{2}$ ton of fuel for every ton of nitrogen fertilizer. Even at 1976 oil prices, the cost of the fuel amounted only to 10% of the additional crop yields due to fertilization (Revelle, 1976).

A legume plant has two options: either to make roots to take up soil N, or to make nodules to fix atmospheric N_2 . To make roots requires a smaller investment in N than to make nodules; therefore the latter alternative is only beneficial when N levels in the soil are low. An additional advantage of making more roots is that more nutrients and water can be absorbed by the plant (Sprent, 1985).

In addition to cost in energy, there is also a cost in water incurred for every molecule of CO_2 fixed during photosynthesis: water is lost during gas exchange and used for carbohydrate production. Therefore, the use of photosynthate for N_2 fixation is linked to the use of water, and the costs in water may be more significant in low-latitude dry regions than energy costs (Sprent, 1985).

In brief, the legume plant has to pay a substantial price in the form of carbohydrate supply for nodule growth and nodule respiration. Hume (1978) has estimated that 10

to 20% of the potential yield of legumes is lost to dinitrogen fixation. This may be one reason why the yields of legumes are relatively low and have shown greater resistance to breeding for high yields than the grain cereals receiving adequate supplies of nitrogen.

Not only are yields of grain legumes generally low, in comparison to N-fertilized cereals grown under similar conditions, but the yields of cereals grown after grain legumes are generally depressed. Lyon (1936) showed that after grain legumes, the soil nitrogen content was markedly reduced, and the yields of cereals depressed by over 50%.

The foregoing does not apply to forage legumes, harvested before seeds are produced. If the plants are cut for forage or grazed, carbohydrate supply to the nodules is interrupted, the nodules degenerate, and nitrogen is released into the soil. With regrowth, nodulation and N_2 fixation recommence; Sprent (1985) notes that this pattern of nodule loss and regrowth in shrubby legumes may result in more nitrogen being fixed per ha than if the plants had not been harvested. Therefore, the value of a forage legume, included in the rotation as a provider of atmospheric nitrogen, making possible a considerable saving in energy inputs for the following crops, is an important consideration in appreciating the energy costs of the forage.

However, in tropical regions, legumes appear to be less capable of fixing dinitrogen than in temperate and subtropical regions, and do not always carry bacterial nodes. In most parts of Africa, legumes have not proven to be better than grasses or weeds in restoring or maintaining soil fertility (Webb, 1960). These findings were confirmed by Moore (1962), who found that the amounts of dinitrogen fixed were rarely significant, and then only after mineral fertilization.

Prospects

Great hopes are placed on research aimed at inducing micro-organisms to perform a symbiotic relationship with cereals, similar to that with legumes, or even to transfer the genetic capability for nitrogen fixation directly from bacteria to plants. It is estimated that the potential benefit of such research, if successful, would make it possible for cereals to fix biologically an amount of nitrogen more than five times greater than the current consumption of nitrogen fertilizers by the developing countries. "Extrapolating from current yield data in the developing countries, this amount of biologically fixed nitrogen could produce 200 million ton of grain, more than half the current output of the developing countries (excluding China)" (NAS, 1976). However, these figures do not take into account the probable yield reduction due to energy demands on the plant for biological dinitrogen fixation. La Rue and Patterson (1981) conclude that "ultimately, plant breeders and agronomists will require accurate estimates of the amount of fixation, and of its cost, to determine whether increasing fixation is economically justified".

At best, symbiotic N_2 fixation can make it possible to reduce N fertilizer use, without a dramatic loss in yield (Marschner, 1986).

The situation is different for non-symbiotic N₂-fixing systems. With these, the cultivated crop is not required to pay a price for the nitrogen made available. Though the significance of these systems in natural environments is often questioned, Curl and Truelove (1986) state: "it seems certain that this process contributes considerably to the maintenance of soil fertility in tropical agriculture". These authors further point out that rice can be grown continuously for many years in the same fields, without supplemental N fertilizer, because the nitrogen removed by the crop is replaced, in part, by non-symbiotic fixation.

Mycorrhizae

The importance of the symbiotic relationship between most higher plants and mycorrhizae in the rhizosphere is being increasingly recognized and large-scale research is being devoted to this subject.

These potentially beneficial organisms occur in all soils; the actual benefit they confer is not yet known sufficiently and is not easy to measure (Abbott et al., 1988).

Wittwer (1980) states that potential benefits that may be derived from inoculation with superior strains of mycorrhizae include enhancement of crop productivity, an expansion of crop production in areas with unfavourable climate and poor soils, and the use of a technology that conserves a non-renewable resource (phosphorus).

Major groups

These symbiotic associations are generally divided into two main groups: the *sheathing* or *ectomycorrhizae*, which contain a fungal mantle surrounding the roots, as well as intercellular growth in the first few layers of the root cortex, and the *non-sheathing* or *endomycorrhizae* which contain a loose fungal network in the soil and the fungus grows in the root cortex (Safir, 1980) (Fig. 10.9).

The endomycorrhizae occur on many cultivated plants, including wheat, maize, cotton, legumes, grasses. The rate of infection is affected by various soil factors: optimal conditions are a slightly acid soil pH, a soil temperature in the range 20–25°C. The infection rate is very low in N-deficient plants (Hepper, 1983).

The mycorrhizal fungus obtains carbon compounds from the host plants, which it transforms into sugars and ultimately to glycogen.

Superior strains of mycorrhizae have been isolated.

Benefits

Mycorrhizae, and in particular the endomycorrhizae and the subgroup named *vesicular-arbuscular mycorrhizae* (VAM), are especially efficient in improving uptake of phosphorus and other low-mobile nutrients by the roots of most food crops. The

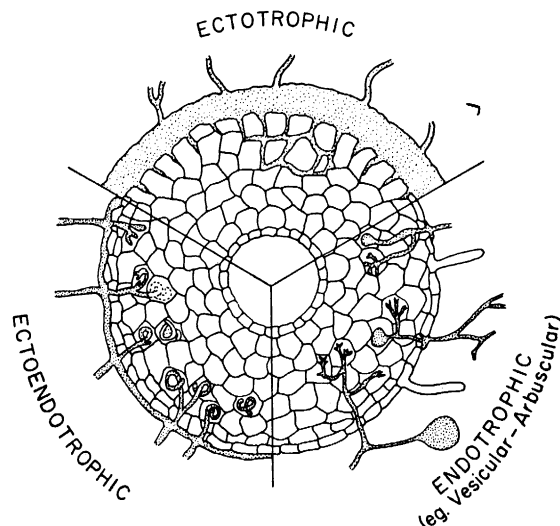


Fig. 10.9. Mycorrhiza types. (a) Ectotrophic: there is a sheath of fungal tissue and limited intercellular invasion by hyphae (the Hartwig net); (b) endotrophic (vesicular–arbuscular as an example): root hair formation is not suppressed and hyphae ramify surrounding soil, producing large spores; (c) ectoendotrophic: some of the coiled, fungal hyphae within the plant cell become digested. From Lynch (1983). By permission of Blackwell Scientific Publications, Oxford.

arbuscules within the plant function as fungal extensions of the roots and act as transfer sites to release carbon and phosphorus; their major function appears to be the provision of the latter in P-deficient soils (Lynch, 1983).

Significant increases in P uptake and growth stimulation are reported for crop species with coarse root systems that are not highly branched; conversely, species which have extensive, highly branched root systems, and long root hairs are hardly or not affected (Marschner, 1986).

Mycorrhizal hyphae can counterbalance a small surface of host roots and can therefore be considered as an alternate root system, especially for P uptake. This dual system of nutrient uptake provides a higher flexibility in response to unfavourable soil conditions, such as pH, moisture level, and temperature stress (Rovira et al., 1983).

Legumes in particular benefit, because in addition to helping roots absorb mineral nutrients, they improve dinitrogen fixation by *Rhizobium*, especially in P-deficient soils. Significant increases in yields of cereals and vegetable crops have been reported. Lynch (1983) suggests that there is a great prospect for soil inoculation in such situations.

Root colonization by VAM fungi of severely P-deficient plants has effects similar to those resulting from P fertilization; and the fungus has therefore been called a biological fertilizer (Bethlenfalvay and Franson, 1988).

A potentially important role of ectomycorrhizae, though still poorly understood, is their ability to deter infections of feeder roots by pathogenic species of *Phytophthora*, *Pythium*, *Fusarium*, and other fungi; the mycorrhizal fungi have also been found to alleviate heavy metal toxicity (Gildon and Tinker, 1983).

Environmental factors

The mycorrhiza-plant association is favoured by a low to medium soil fertility level; in highly fertile soils, especially in those high in P and N, the establishment of mycorrhizae is generally retarded (Safir, 1980).

Mycorrhizal plants are reported to recover faster than non-mycorrhizal plants from moderate moisture stress, apparently as the result of decreased resistances to water transport in mycorrhizal roots. An optimum soil moisture supply for plant growth is also favourable for mycorrhizal infection (Safir, 1980).

Any change in soil conditions, such as resulting from the introduction of exotic plants, cultivation, the use of agro-chemicals, will probably alter the composition and effectiveness of the VAM flora (Howeler et al., 1987).

Soil pathogens

Environmental factors

The presence and abundance of soil pathogens are also an important element of soil fertility, as we have defined it. Whilst the subject will be treated in more detail in Ch. 19, a few aspects directly related to soil factors, and summarized from Palti (1981), will be considered here. The pathogenic components of microflora are fungi, bacteria, and some viruses transmitted by soil organisms; the main microfauna are various parasitic nematodes.

Soil moisture content has a considerable effect on the relations between soil pathogens and their competitors and antagonists. Bacteria are relatively inactive when the soil moisture potential approaches the wilting point, while some important fungal pathogens are still virulent at this moisture level. *Fusarium* wilts and rots occur more frequently on fairly dry, or alternatively dry and wet, soil than on wet soil; Charcoal rots (*Macrophomina phaseoli*) attack many hosts in dry soils.

Moisture stress inhibits infection by root-knot nematodes (*Meloidogyne hapla*); conversely, infestation by root-knot nematodes increases water stress in a number of crops.

The growth stage at which moisture stress occurs has considerable importance: in wheat, for example, drought stress at the jointing stage, increases susceptibility to take-all (*Gaeumannomyces graminis*) as compared with stress at later stages.

Excess water has mainly indirect effects by a general weakening of the host plants:

feeder roots may necrotize, water and nutrient uptake is inhibited by oxygen deficiency; all these factors predispose to infection, even by facultative parasites.

With increasing *soil depth*, oxygen is reduced, with a concurrent increase in CO₂; populations of root-infecting fungi decrease rapidly with depth, and are rarely found below the 50–60 cm level (Palti, 1981).

The most favourable *soil reaction* for actinomycetes, such as *Streptomyces scabies*, which causes potato scab, and for bacteria, is close to, or above neutral. Fungi are less susceptible to acidic conditions, and are therefore better able to compete with bacteria and actinomycetes when pH < 7.

Organic amendments can affect soil-borne pathogens in two ways: (a) by preventing pathogens from establishing themselves in hitherto arid soil by enriching the soil with microflora that is potentially competitive with, or antagonistic to, pathogens that may appear as soon as cropping starts; and (b) by controlling pathogens in the soil: this can be a direct effect on the microbiota or indirect by increasing the availability of nutrients.

Cook et al. (1978) point out that although organic amendments incorporated into the soil in the right amounts and the right time are generally suppressive to root diseases, they may also increase disease, in particular when a crop residue serves as a food source for pathogens such as *Sclerotium rolfsii*, *Pythium aphanidermatum*, and *Phytophthora parasitica*.

Crop residues may release during decomposition various volatile compounds which may stimulate the germination of propagules of certain pathogens, such as *Verticillium dahliae* and *S. rolfsii*, followed by lysis and a net reduction in the population of the fungi. Crucifer residues, during decomposition, produce sulfur-containing volatiles that inhibit certain plant pathogens, such as *Aphanomyces euteiches*, that causes root-rot of peas. Ammonia released during decomposition of organic matter is also inhibitory to the germination of, and infection by, certain fungi. Ethylene, released by the decomposition of organic matter inhibits germination of sclerotia of *S. rolfsii*, and reduces *Fusarium* wilt in tomatoes (Cook et al., 1978).

Fresh organic material (weeds, green plant residues, green manures) is more immediately available to colonization by pathogens than by saprophytes, therefore the use of dead plant residues is safer where infection by fungi such as *Pythium* spp. or *Phytophthora parasitica* is to be expected.

Some sclerotia, such as those of widespread polyphagous pathogens, and other resting bodies of fungi can survive passage through the digestive tracts of animals; fresh farmyard manure is therefore a source of infection. Composting may reduce this danger, without completely eliminating it.

Burying inoculum-carrying organic residues below the normally ploughed layer, removes it from the major site of infection without killing the inoculum. Sclerotia and other resting bodies can survive such burial for long periods.

The addition of organic matter to the soil increases the population of fungi, predaceous nematodes, and internal parasites that attack soil nematodes.

Biological balance

The struggle for survival between the micro-inhabitants of the soil, is no less severe than that proceeding above-ground among larger organisms.

“Biological complexity of the soil assures associative, competitive, and antagonistic relations which limit population explosions and thus brings about balance” (Wilhelm, 1965).

Normally, a balance between saprophytes and parasites is maintained in the soil. When ample organic matter is applied to the soil, saprophytes are generally favoured and they may compete successfully with parasites. For example, many soil bacteria have been shown to inhibit the growth of the pathogens causing take-all diseases of wheat (Fellows, 1929), *Phymatotrichum* root-rot of cotton (King et al., 1934), and the wilt diseases of a number of crops – such as cotton, melon, and flax – due to *Fusarium oxysporum* (Mitchell and Alexander, 1961). However, in the absence of a sufficient supply of dead organic matter, even saprophytes may attack living plant tissues.

Experience has shown that, if a plant which is susceptible to root disease is grown in a sterile soil and then inoculated with a pathogen that causes root-rot, it will be more severely infected than if the soil had not been previously sterilized. Root diseases are more prevalent in soils that are poor in saprophytic flora than in those with an abundant population of saprophytes. The saprophytes reduce the numbers of pathogens in the soil by (a) preying on the pathogens, (b) competing for nutrients, oxygen, etc., and (c) excreting substances that are toxic to the pathogens (antibiosis). For the antagonists to be effective in biological control, they have to build up sufficiently high populations, and environmental conditions must be favourable to them. The addition of appropriate crop residues is one of the means of achieving this aim. Yet results are not always consistent: e.g., the decomposition of the residues of a leguminous crop was found to depress the survival of *Helminthosporium sativum*, but to enhance that of *Ophiobolus graminis* (Garrett, 1970). Residues may even have entirely different effects on the same pathogen, depending on the condition and stage of their decomposition; the pathogen population may increase initially, but become more and more depressed as decomposition progresses – presumably as a result of nitrogen starvation due to the increased competition of the saprophytic population (Patrick and Tousson, 1965).

The addition of organic manures causes a rapid increase in the populations of certain predaceous fungi which are capable of trapping and feeding upon eelworms, whose numbers are thereby reduced (Duddington, 1955).

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CHAPTER 11

Mineral Plant Nutrition and Fertilizer Use

Plant nutrients

Although the main nutrient elements in the soil have been dealt with briefly in Ch. 10, the subject will be treated in more detail in this chapter, with special reference to the significance of mineral nutrition to crops in general, and the use of fertilizers in rainfed and irrigated agriculture in dry regions in particular.

Nitrogen

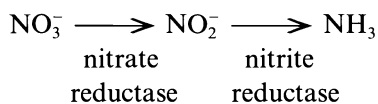
Role

Nitrogen plays a vital role in all the living tissues of plants. It constitutes up to 2–4% of the dry weight, a very low level when compared with the carbon content, which is about 40% (Mengel and Kirkby, 1982).

No other element has such an effect in promoting vigorous plant growth. A deficiency of other elements may have as great a detrimental effect as N, but the response of most crops – excepting legumes – to fertilizer N is usually more striking, visually and rapidly, than is the case with other fertilizer nutrients.

Higher plants convert mineral N into organic compounds; the major inorganic sources involved in this conversion are nitrate (NO_3^-) and ammonium (NH_4^+).

Most of the ammonium is incorporated into organic compounds in the roots; the nitrate is mobile in the xylem and can also be stored in the vacuoles of roots, shoots, and storage organs. However, before the nitrate ions can be incorporated into organic structures, they have to be reduced to ammonia, in a two-way process:



The ammonia is subsequently built into more complex compounds, and ultimately into proteins and nucleic acids.

Nitrogen alters plant composition more than any other mineral nutrient. Increasing the supply of N results in an increase in all N compounds in the plant, but the increase is differential between free amino acids, amides, amines and proteins. The content of the soluble amino compounds increases more steeply than that of proteins with increasing rates of N application. This signifies that inorganic N is assimilated more rapidly than the amino acids are being used for protein synthesis (Mengel and Kirkby, 1982).

High levels of N in the root zone during early growth enhance elongation of shoots and inhibits that of roots; these morphological changes are unfavourable for nutrient and water uptake in later growth stages (Marschner, 1986). In cereals, the susceptibility to lodging is thereby increased, and this can become the dominant yield-limiting factor.

Forms of nitrogen nutrition

Uptake of N by crops is mainly as nitrate; whatever the form in which it is carried in fertilizers, rapid nitrification of available ammonia occurs when soil conditions are favourable for plant growth (Fig. 11.1).

Notwithstanding the rapid change of ammonia to nitrate in the soil, the form in which N is taken up by plants has considerable practical importance. It has a marked effect on carbohydrate production, and thereby on the cation–anion balance.

Contradictory effects of the two sources, nitrate and ammonium, have been reported. Marschner (1986) notes that this is to be expected, in view of the different effects of the two ions on the cation–anion balance, on root-induced pH changes in the rhizosphere, and on energy metabolism. Ammonium generally inhibits cation uptake and can depress growth by inducing a deficiency of Mg or Ca. The detrimental side-effects of ammonium are of minor importance in well buffered soils with a pH

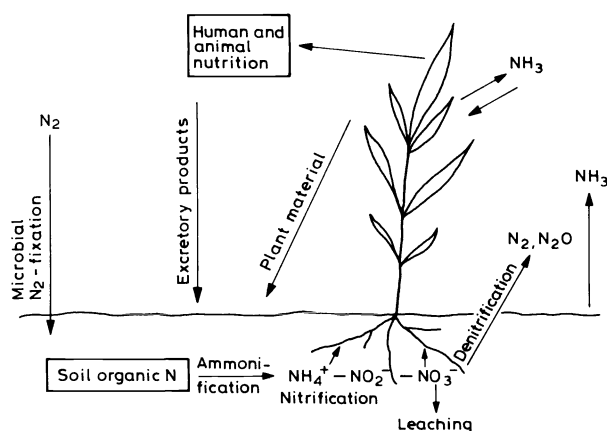


Fig. 11.1. Nitrogen cycle in nature. Mengel and Kirkby (1982). By permission of the International Potash Institute.

in the range 5–7; but can be detrimental to growth in soils with either a very low cation-exchange capacity or with pH values below 5, or above 7.

Kafkafi and Halevi (1974) found that a high mineral NO_3 N level in the soil decreased the ability of wheat to absorb P during the early stages of plant growth. The suppressive effect on P uptake persisted as long as more than about 90 kg/ha NO_3 N were present in the upper 40 cm soil layer. A similar depressing effect of nitrate on P uptake was observed for maize (Bar-Yosef and Kafkafi, 1972).

Nitrification practically ceases in air-dry soils, but can still take place at wilting point. The optimum soil moisture content for nitrification corresponds to a suction of -0.5 bar (Miller and Johnson, 1964).

Under alkaline conditions, and especially in the calcareous and alkaline soils frequently found in the dry regions, the oxidation of ammonia into nitrate proceeds more rapidly than the subsequent oxidation of nitrite into nitrate, so that relatively high concentrations of nitrite, which is toxic to plants, may result (Hagin and Tucker, 1982).

Such concentrations of nitrites may occur under relatively anaerobic conditions and with a high microbial activity in the rhizosphere; under these conditions nitrate is used instead of oxygen as a hydrogen acceptor. Irrigation during hot periods can produce conditions favourable for denitrification (Kafkafi, 1973). Kafkafi and Bar-Yosef (1971) found that irrigated maize, on a montmorillonitic clay soil, lost 330 kg/ha NO_3 N within 35 days, most of which was lost in the course of 14 days following sprinkler irrigation of 68 mm.

Clarkson and Warner (1980) have shown that for any given plant species, the uptake and utilization of ammonium is greater at low temperatures than that of nitrate, when the two ions are supplied in equal concentration.

In a review of past and current research on the subject, including his own work, Kafkafi (1990) concludes that ammonia can be a very good source of nitrogen to the plant if it is supplied to the roots in low concentrations. The major point to be considered is that the supply should not cause an excessive load on the sugar content of the roots.

For intensive crop production, nitrate is a safer source at higher temperatures in the root zone, while ammonia is a better source when root temperatures are low.

The effect of urea on plant metabolism and growth is intermediate between that of nitrate and of ammonia. Urea is rapidly hydrolyzed by urease either in the soil, or after being taken up by the roots or absorbed by the leaves (Mengel and Kirkby, 1982).

Nitrogen requirements of crops and limitations in use

Nitrogen requirements vary considerably at different stages of development of the plant: minimal in the early stages, the requirements increase as the rate of growth accelerates, to reach a peak in most crops during the period between the onset of flowering and early fruit or grain formation.

There are quite a number of cases in which the application of the full amounts of nitrogen fertilizers, that are required for maximum yields, may have undesirable side-effects.

In certain plants, such as small-grain cereals and maize, excessive nitrogen increases the proportion of straw to grain, and in combination with succulent growth, is conducive to 'lodging' of the tall but weak straw. In cotton, the excessive vegetative growth hinders mechanical harvesting and makes the crop more susceptible to insect attack. In sugar beets, high levels of nitrogen reduce the sugar content and increase the amount of noxious nitrogen in the roots, which impedes sugar crystallization. In malt barley, malting quality, as measured by the percentage of malt extract, will usually be reduced if nitrogen is applied for maximum grain yields. The undesirable effects of high levels of N fertilization can be alleviated by proper timing of application and, particularly, by a well-balanced supply of potassium and phosphorus.

Commercial nitrogenous fertilizers

The bulk of the chemical nitrogen compounds are ammonia derivatives, produced synthetically – mainly by reacting nitrogen and hydrogen gases. The basic compound NH_3 can be used either directly or after transformation into many other commercial N carriers.

Ammonium fertilizers. These have a specific advantage for agricultural use in the arid regions: the NH_4^+ ions are mostly adsorbed by the electronegatively charged colloidal fraction of the soil, some stay in the soil solution, and some may be fixed into the lattice of clay crystals. Ammonium is therefore less liable to leaching in irrigation agriculture than are the nitrates. Furthermore, ammonium uptake is best in typical dry-region neutral and alkaline soils, and is depressed as the pH is lowered; the converse is true for nitrate (Mengel and Kirkby, 1982). However, when ammonium salts are applied to the surface of alkaline or calcareous soils, very unstable ammonium carbonate or ammonium bicarbonate salts are formed. These decompose, and so free ammonia may be lost. The higher the temperature, the greater the possible losses.

Ammonium sulfate (20.5% N, 23.4% S) was the most widely used nitrogenous fertilizer in the dry regions.

Its marked tendency to acidify the soil is a disadvantage in temperate and tropical climates, whose soils tend toward a low pH in any case, and its continued use under these conditions makes periodic liming essential. However, this is usually not the case in the soils of arid regions, and the sulphur provided by the fertilizer may frequently be beneficial as a nutrient in its own right.

Ammonium sulphate has good physical properties for storage, handling, and application; its main disadvantage is the relatively low N content, compared to, for example, urea.

Ammonium nitrate (32–33%) is very soluble in water and very hygroscopic in its

pure form, and therefore tends to cake very easily. Coating the fertilizer particles with inert materials such as kaolin, gypsum, etc., reduces or eliminates the caking.

Under normal circumstances, ammonium nitrate is stable, but when heated, and especially in the presence of organic impurities, it may explode.

When ammonium nitrate is mixed with limestone, a fertilizer called Nitrochalk, with an N content of 20–33% is produced (Hagin and Tucker, 1982).

Ammonium chloride is not widely used, except on paddy rice, where it generally replaces ammonium sulfate. The latter is undesirable because under anaerobic conditions, the sulfate may be reduced to the toxic compound dihydrogen sulfide (H_2S).

Liquid fertilizers. The use of liquefied anhydrous ammonia and aqua ammonia has expanded considerably in a number of countries. As the ammonia is obtained in the first stage of the manufacture of nitrogenous fertilizers, it can be delivered at a much lower price within a reasonable distance from where it is manufactured. It then has further advantages in that no physical effort by the farmer is involved; instead of having to empty heavy sacks into his fertilizer distributor, he moves liquid fertilizer from the transport tanks to the field applicator by pump or compressed air. Moreover the fertilizer distribution in the field, not being affected by wind, is also more uniform than is the application of solid fertilizers.

Nitrogenous liquid fertilizers can be divided into three types, according to the amount of pressure required in the tanks, and the equipment used for storage, transport, and application:

(i) *High pressure: anhydrous ammonia:* Anhydrous ammonia contains the highest percentage of nitrogen (82%) of any of the commercial fertilizers available. Relatively high pressure is required to maintain the ammonia as a liquid, and the higher the temperature is, the greater will be the pressure required. The use of refrigerating equipment to liquefy the ammonia gas and keep it liquid has made possible the replacement of high-pressure tanks.

When no longer under pressure, ammonia gas volatilizes rapidly; nitrogen losses in the field can, however, be avoided by proper application methods. In heavy and medium-textured soils, applying the ammonia to the soil by injection, through tubes running down the rear of a blade-type applicator, to a depth of 15–18 cm, will effectively prevent losses of gaseous ammonia. In lighter soils, the depth of application must be increased slightly.

The ammonia is effectively retained by the colloidal fraction of the soil. Losses may, however, occur if the physical condition of the soil during application is not satisfactory – especially if it is not in good tilth and contains many clods.

As free ammonia is toxic to micro-organisms, their numbers in the soil are initially depressed following its application; however, nitrification is subsequently stimulated, probably as a result of the more rapid recovery of nitrifying bacteria as compared with soil fungi (Eno and Blue, 1954).

Cold-Flo is a more recent method of applying anhydrous ammonia to the soil. In this method, the ammonia is released from a flow regulator into a converter where it expands to near atmospheric pressure and cools down to -33°C . The cooling converts about 85% of the ammonia to a cold liquid which flows out of the chamber through lines to the soil where it is released in the usual manner.

The Cold-Flo system makes it possible to apply ammonia at shallower depths, with fewer sealing and retention problems (Hagin and Tucker, 1982).

Application: Anhydrous ammonia is frequently applied in conjunction with tillage operations such as ploughing or chiseling. Because of the toxicity of free ammonia to plants, it is desirable to apply the fertilizer about two weeks ahead of sowing close-planted crops, such as wheat. For wide-spaced crops, damage to germinating seeds and seedlings can be avoided by placing the band of ammonia 8–10 cm below, and to the side of, the seed row.

(ii) *Low pressure: aqua ammonia:* Aqua ammonia is a solution of ammonia in water, with a nitrogen content of at least 20%. A certain amount of pressure is required to offset the natural tendency of the aqueous ammonia to change into anhydrous ammonia. The application of aqua ammonia can be made closer to the surface than that of anhydrous ammonia, but must be at a depth of not less than 10–15 cm.

(iii) *Non-pressure solutions:* Solutions containing dissolved ammonium nitrate or urea, but no free ammonia, can be applied with very simple equipment in a variety of ways – on the soil surface, injected into the soil, or metered into the irrigation water.

Safety measures: Special precautions must be taken when handling anhydrous ammonia. Exposure to the liquid or vapour can cause severe burns and even blindness; excessive inhalation can damage the lungs, or even cause suffocation. It is essential to have large quantities of water available when handling ammonia (Hagin and Tucker, 1982).

Nitrate salts. Fertilizers belonging to this group are very soluble, and their nitrogen is readily absorbed by the plants without undergoing any transformation. They are, however, very easily leached from the soil.

The principal nitrate sources are sodium nitrate (16% N), potassium nitrate (13.8% K, 36.5% N), and calcium nitrate (15.5% N). They are not acid-forming, and have no special advantages for crop cultivation in arid regions. The most widely available form – sodium nitrate – is even undesirable in irrigation agriculture, because of the sodium component. Ammonium nitrate has already been mentioned in the former group of ammonized fertilizers.

Urea. Since the 1970's, the use of urea has been increasing rapidly. It is popular because of its low cost and high N content and because it is not explosive or corrosive like its nearest competitor – ammonium nitrate. It also blends well with phosphates and potash, especially in the granular form (Hagin and Tucker, 1982).

When applied to the soil, the urea is hydrolized within two to three days by the enzyme urease to form ammonium carbonate, which is then hydrolized into ammonia and CO_2 . The absorption of the ammonia by soil and water generally prevents major losses of nitrogen.

The activity of urease depends on organic matter, cation exchange capacity, clay content and CaCO_3 concentration. Therefore, light calcareous soils, low in organic matter, such as those common in arid and semi-arid areas, have very low urease activity. Saline and sodic soils also have low urease activity; consequently, toxic levels of nitrites may occur.

Urea can be applied as a basic dressing, broadcast and tilled into the surface of the soil, side-dressed, top-dressed as well as by foliar application (Hagin and Tucker, 1982).

Slow-release N fertilizers. In recent years, much attention has been devoted to the development of nitrogen fertilizers in which N is released gradually into the soil, thereby assuring a gradual supply to the crop, reducing losses due to leaching and denitrification and avoiding luxury consumption in the early growth stages.

Urea formaldehyde (ureaform) is a reaction product of urea and formaldehyde. It consists of a mixture of methylenurea polymers differing in chain length and molecular weight. The shorter the molecular chain, the more easily the N becomes soluble.

In most commercial ureaforms, the N is more or less equally distributed between three fractions; the shortest fraction is the first in which N becomes available; N is released more slowly from the second fraction, and the N of the third fraction is considered as unavailable to the crop (Hagin and Tucker, 1982).

The decomposition of the polymers is a microbial process and therefore the rate of N release is dependent on soil conditions, such as temperature, moisture, pH, etc. N availability is not necessarily synchronized with the demand of the growing crop; it may be available at a period of low demand, and in short supply at peak demand. Consequently, slow-release fertilizers are not always more efficient, and may occasionally even be less efficient sources of N than the conventional fertilizers (Power, 1979).

Sulfur-coated urea: in this fertilizer, the urea is coated with a combination of sulfur, a sealant material and a microbicide. N is released from the granules as and when their cover cracks, thereby allowing urease to penetrate the granule and to hydrolize the urea into ammonia.

Urea release from sulphur-coated urea is faster in warm climates; because it is unaffected by salinity it might be a suitable source of N under saline conditions (Oertli, 1973).

In the many trials in which the slow-release ureas were compared with conventional urea, the former showed some advantage only under conditions conducive to severe leaching, such as high rainfall during the growing season, or during the period between fertilizer application and sowing.

Nitrification inhibitors, such as *N-serve* consist of a mixture of a conventional N fertilizer with a nitrification inhibitor. Like the sulphur-coated urea, *N-serve* may be useful under conditions conducive to severe leaching. However, it is difficult to predict how long the nitrification inhibitor will remain effective, as it may be lost by leaching, evaporation, and mainly by biological decomposition. The rate of decomposition will depend on environmental conditions, and may occur at an unsuitable time (Touchton et al., 1978).

The price per unit of N is higher for the slow-release fertilizers currently available, and they have only shown some advantage in special circumstances (Hagin and Tucker, 1982). Under the present circumstances, their use on a commercial scale for field crops is probably limited.

Protein fertilizers such as dried blood or dried fish-meal were of historical interest only, until their use has been renewed by organic farmers.

Phosphorus

Total P levels are generally lower in semi-arid soils as compared to soils in other regions, but availability appears to be higher, excepting in calcareous soils (Tucker, 1988).

Plant roots are capable of absorbing phosphate from the soil solution with very low concentrations of P. Generally, the P content of root cells and xylem sap is from a hundred- to a thousandfold higher than that of the soil solution, indicating that P is taken up by the root cells against a very steep concentration gradient (Mengel and Kirkby, 1982)

The quantities of P that are present in the tissues of most plants are much smaller than those of the other two major nutrients, N and K, being only one-tenth of the N, and one-fifth of the K, when expressed in percents of dry matter.

Most of the P is absorbed by the plant in the form of orthophosphate ions – mainly the primary orthophosphate anion H_2PO_4^- and, to a much lesser degree, the secondary orthophosphate ion HPO_4^{2-} .

Phosphate is very mobile in the plant; after it is absorbed by the plant cells it is incorporated extremely rapidly into organic compounds (Mengel and Kirkby, 1982).

Unlike nitrate and sulphate, phosphate is not reduced in plants after its uptake, but remains in its highest oxidized form, either as inorganic phosphate, or in organic forms: such as phosphate esters (e.g. sugar phosphate) or attached to another phosphate by an energy-rich pyrophosphate bond [e.g. in the coenzyme adenosine triphosphate (ATP)]. Inorganic phosphates predominate in the cell vacuoles (the non-metabolic pool), whereas phosphate esters predominate in the cytoplasm and chloroplasts (the metabolic pool).

Inorganic phosphate is released from the vacuoles very slowly; in addition to its role in the nonmetabolic pool, as a major constituent of nucleic acids, it has various

essential regulatory functions in photosynthesis and carbohydrate metabolism of leaves (Marschner, 1986).

Although present in the cell in very small amounts, phosphate esters are intermediates in metabolic pathways of biosynthesis and degradation. Their function is directly related to energy metabolism of the cells and to energy-rich phosphates (Marschner, 1986).

The unique function of phosphate in metabolism is its formation of pyrophosphate bonds which allow energy transfer, and are required for all biochemical processes which need energy, such as the synthesis of sucrose, phospholipids, cellulose, and nucleic acids. ATP is the most important of these compounds (Mengel and Kirkby, 1982).

Phosphorus requirement for optimum growth is from 0.3 to 0.5% of plant dry weight during vegetative growth. P deficiency reduces most metabolic processes, including cell division, respiration, and photosynthesis. Growth is retarded and in particular root hydraulic conductance is reduced (Radin and Eidenbock, 1984).

During growth, phosphorus concentrates mainly in the plant tissues in which cell division is proceeding actively. It is an essential constituent of nucleic acid, of phytin, and of phospholipids. An adequate supply of easily available phosphorus is of great importance during the early stages of growth when the limited root system is not yet capable of drawing sufficiently on the phosphorus reserves of the soil and cannot effectively compete with soil micro-organisms for the available phosphorus.

A deficiency at this stage adversely affects the laying down of the primordia for the reproductive parts. High doses of phosphorus, when available to young maize plants, were also found to enhance the rate of nitrogen metabolism (Pleshkov, 1956). Adequate phosphorus, supplied at a later stage, therefore cannot remedy the adverse effects of a deficiency at the critical earlier stage.

The level of P supply during the reproductive stage is critical: it regulates the starch/sucrose ratio in the leaves and the supply of photosynthates to the reproductive organs (Giaquinta and Quebedeaux, 1980). A P deficiency results in a delay in flower initiation (Rossiter, 1978) and a reduction in the number of flowers (Bould and Parfitt, 1973). Therefore, under conditions of P deficiency, not only are yields depressed, but fruits and seeds of poor quality are produced (Mengel and Kirkby, 1982).

Conversely, an excess of P is undesirable for wheat, under conditions of limited moisture supply, because it encourages the production of sterile tillers, which deplete water essential for grain production (Kafkafi et al., 1978).

Fixation of phosphorus

The process whereby soluble phosphates, as applied in fertilizers, are changed into less soluble forms in the soil, is called 'fixation' or 'reversion'. The nature of fixation may affect the efficiency of different forms of fertilizer P differently, according to soil type.

Phosphate fixation in alkaline and calcareous soils is mainly due to the formation of insoluble compounds of Ca; some fixation may be due to the aluminium in the clay fraction of alkaline soils, and, to a minor degree, to the activity of micro-organisms (Hemwall, 1957).

The clayey-textured Oxisols, which have a very large surface area of fine clay particles and secondary iron oxide, inactivate every form of P added as fertilizer. This fixation capacity is estimated at 5–10 kg/ha P for each 1% clay in the plough layer. It can often be overcome by a single application of 200 kg/ha P; thereafter, annual maintenance applications of 25 kg/ha P are necessary (Buol and Sanchez, 1988).

A capacity for P fixation as high as 312 mg/kg has been reported for India's Al-fisols, whose native extractable P levels seldom exceed 13 mg/kg (El-Swaify et al., 1984).

The amount of phosphorus that needs to be applied to a phosphorus-deficient soil is usually far in excess of the immediate requirements of the plant, because of the rapid fixation of the phosphorus in the soil. Larger doses are therefore needed, in order to saturate the fixing power of the soil and leave an excess available to the crop. For example, land-levelling required prior to irrigation may expose calcareous or extremely infertile subsoils that are poor in phosphorus. It has been shown that extraordinarily large amounts of phosphorus – up to 140 kg of P per ha – may increase the productivity of these soils markedly, even to the same level as that of the unexposed soil. This effect may already be evident in the first season after exposure, provided N and Zn are also added (James et al., 1967).

Two factors influence the supply of phosphorus to the crop:

- (a) The concentration of phosphorus in the soil solution; this is mainly important for the young plant.
- (b) The concentration of phosphorus in the soil, and its capacity to ionize and thereby maintain the level of phosphorus in the soil solution. This is the main source of supply for the developed plant.

In soils in which 'fixation' of phosphorus occurs, only a small proportion of the fertilizer phosphate (usually not more than 5–15%) may be taken up by the crop to which it is applied. However, as we have already seen, the remaining phosphate is not lost. A distinction must be made between non-solubility and non-availability of the phosphorus, as the rapid fixation does not prevent the fertilizer phosphorus from contributing gradually to the replacement of phosphorus in the soil solution.

The fertilizer phosphorus that is not taken up by the crop to which it is applied should be considered as a capital investment; remaining as it does in the 'labile ionic pool', its presence will enable the next addition of phosphate to increase the potential to a greater extent than would have been the case otherwise (Russell et al., 1961) (Fig. 11.2).

Soil erosion can cause considerable losses of P from the upper soil layer.

The process whereby response to P fertilization declines progressively as the result

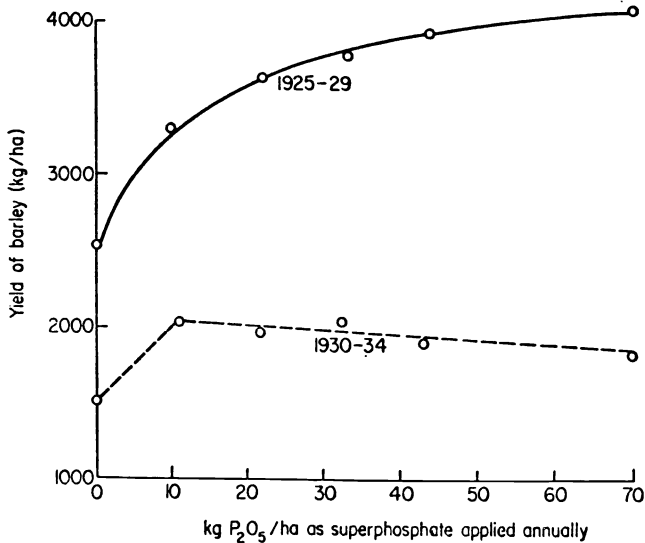


Fig. 11.2. Response of barley to increasing rates of superphosphate application during two successive periods. During the initial period (1925–1929) the P status of the soil was low, but available-N status was relatively high. During the second period the soil P status had improved as a result of the high rates of superphosphate applied during the previous period, but available N had been reduced by cropping – hence overall yields during the second period were low and there was no response to superphosphate on areas that had previously received annually 20 kg/ha or more of P₂O₅. After Woodroffe and Williams (1953). By permission of the Australian Journal of Agricultural Research.

of build-up of reserves may also be reversed, as described by Tucker (1989). During the initial years of wheat fertilizer tests in the 1950's, in western Oklahoma, responses to added P were commonly obtained; in the 1960's responses to P fertilizers became rare. Widespread adoption of N fertilizers by growers began in the late 1950's; yield increases caused a depletion of soil P, and by the 1970's yield increases from added P again became common, and even more dramatic than those obtained previously.

Phosphorus fertilizer application

Movement of phosphorus in the soil. Owing to the rapid fixation of phosphorus, there is very little natural downward movement of this element in the soil. With irrigation, the downward movement of phosphorus is increased, the depth of penetration being proportional to the amount of water applied (Jordan et al., 1952). However, even with irrigation, the downward movement is limited. It has been found that after 28 years, 80% of the P fertilizer applied to an irrigated soil remained in the top 30 cm of the soil and very little had penetrated beyond 60 cm. It is therefore frequently recommended to incorporate phosphoric fertilizer into the soil by ploughing. This has several disadvantages, however: the emerging seedling does not find sufficient available phosphorus and is hindered in its development, and by the time

its root system has developed sufficiently to exploit the soil efficiently, the phosphorus is no longer readily available. Moreover, phosphate applied in this way is exposed to a great surface of contact between soil and fertilizer, and fixation is rapid and complete.

The availability of P is also dependent on soil temperature, as roots develop more rapidly when temperature conditions are favourable.

Minimizing contact with the soil. Minimizing the contact between phosphate particles and the soil may reduce fixation.

Granular P fertilizers are often recommended for general farm practice because of reduced fixation due to the smaller surface area involved; however on alkaline soils, where the immobilization of P by Al and Fe is of minor importance, finely powdered fertilizers, with highly soluble P, are more effective than granulated fertilizers (Hagin, 1958).

Foliar application of phosphorus is not a widespread practice, but it is claimed to be more economical under certain circumstances than applying to the soil (ibid.).

Soaking seeds in phosphate solutions has been reported to increase P uptake and improve yields in a number of crops, presumably by stimulating very early root development (Hagin and Tucker, 1982).

Starter fertilizers containing P often give unsatisfactory results on soils of high inherent P supply. This has been attributed to overstimulation of early growth, which accentuates the damage caused by drought that occurs at later stages of growth. In other cases, the earlier physiological maturity was disadvantageous, when the critical stage of the reproductive cycle coincided with hot, dry weather (Warder et al., 1963).

Banding. Banding P fertilizers for annual crops will be discussed in another section (cf. p. 556).

Perennial crops, such as lucerne and permanent pastures, are a special problem. The phosphate can only be broadcast on the soil surface and, at the most, lightly disked in. Experience has shown that downward movement of phosphorus, under these conditions, does not exceed a few centimetres, even after a year or longer. However, it has been proven conclusively that topdressed phosphates are highly beneficial to crops that require annual applications of phosphorus. In parts of Australia, it was found that broadcasting superphosphate on the surface of pastures was just as beneficial as drilling it in (Ignatieff and Page, 1958).

*Phosphate fertilizers**

In the 19th century the main source of fertilizer phosphorus was finely ground animal

*The calculation in commercial use of available phosphate in fertilizers is based on P_2O_5 . Most scientists appear to prefer elemental P percentage to express fertilizer phosphorus (note $P \times 2.2 = P_2O_5$; $P_2O_5/0.45 = P$).

bones. Liebig (1843) was able to show that treating the bones with sulphuric acid increased the availability of the phosphorus. It was J.B. Lawes in England, however, who developed the treatment of rock phosphate by sulphuric acid into an industrial process for the production of superphosphate.

Phosphoric acids. There are two kinds of phosphoric acids: ortho or poly, depending on their degree of polymer condensation. Agricultural grade orthophosphoric acid, H_3PO_4 , containing 55% of P_2O_5 , is used mainly in the manufacture of triple superphosphate or ammonium phosphates. It can, however, be applied directly to the soil by injection, or be added to irrigation water, and is particularly effective in the alkaline and calcareous soils that are typical of many arid lands.

Superphosphoric acid, containing from 69 to 76% P_2O_5 , can be used for direct application, but it is not widely used.

All the phosphoric acids are corrosive and difficult to handle.

The superphosphates. These are the most important commercial phosphate fertilizers, and consist of calcium orthophosphate. The three commercial fertilizers are ordinary or single superphosphate (16–22% of P_2O_5), enriched superphosphates (25–30% of P_2O_5), and triple superphosphates (44–52% of P_2O_5). The superphosphates have no appreciable effect on soil pH. The single superphosphate consists of a mixture of monocalcium phosphate and gypsum in approximately equal amounts. The gypsum may be beneficial in its own right, especially on alkaline irrigated soils. The triple superphosphate is advantageous in areas in which transport costs are significant: in granular form, it is convenient to handle and fixation is retarded. However, under dry conditions, the powdered forms usually give the best results (Tisdale and Nelson, 1966).

Ammonium phosphates. These are more water-soluble than the superphosphates. Fertilizer grade mono-ammonium phosphate contains approximately 11% N and 48% P_2O_5 ; di-ammonium phosphate 16% N and 46–48% P_2O_5 .

The ammonium phosphates are very popular because of their low hygroscopicity, low tendency for caking and their high content of essential plant nutrients makes their transport, storage, and handling, more economical than is the case with most of their rivals. However, on alkaline soils they may release free ammonia, which is toxic to young seedlings. Proper precautions should therefore be taken in regard to placement in relation to the seed rows. Ammonium phosphates have an acidifying effect on the soil.

Field experiments in which ammonium phosphates, phosphoric acid and superphosphate were compared, showed little differential effects on plants (Dungarwal et al., 1973).

*Potassium**Role*

Though K is the only mineral nutrient (besides, possibly, chlorine) that is not a constituent of important plant components such as protoplasm, fats, and cellulose, an essential role has, at one time or another, been ascribed to this element in almost every important physiological process of the plant. Potassium functions mainly in osmoregulation, the maintenance of electrochemical equilibria in cells and the regulation of enzyme activities (Marschner, 1986). There are more than 50 enzymes which either completely depend on, or are stimulated by K^+ (Suelter, 1970).

Most of the K requirement of the plant is during the vegetative stage (e.g., in cereals – from tillering to ear formation). K^+ uptake is in competition with other cations, and vice versa.

The role of K in the water status of the plant is of major significance for crops grown in dry regions.

In young tissues, K^+ is indispensable for optimum cell turgor (Arneke, 1980). K^+ plays a key role, as the most important inorganic osmotic solute in the vacuole, in maintaining a high water level in the plant tissues, even under water stress. When soil water is limited, loss of turgor and wilting are typical symptoms of K deficiencies (Marschner, 1986).

The major contribution of K^+ to drought tolerance is by reducing water losses due to transpiration, through the role of K^+ in stomatal regulation: in most plant species K^+ has the major responsibility for turgor changes in the guard cells whereby stomatal opening is regulated (Humble and Hsiao, 1970). This is a major mechanism controlling the water régime of higher plants.

The application of adequate amounts of K fertilizer was found to be more effective in improving the moisture status of sugarcane, than was a reduction of the interval between irrigations (Barber and Humbert, 1963). Soil moisture is used more efficiently when K is plentiful, especially in periods of drought, than when it is deficient. Potassium deficiencies prevent the normal ripening of cereals and result in shrivelled grain, while applications are particularly effective on crops that are grown for starch or for sugar.

For a detailed discussion of the role of K in plant physiology the reader is referred to Mengel and Kirkby (1982) and/or Marschner (1986).

Potassium requirements

As potassium is involved in so many vital processes, an adequate supply to the plant of available potassium is essential. Leigh and Wyn Jones (1984) suggest that the concentration of K in the cytoplasm must be maintained at a level of about 150 mM and that in the vacuole at a minimum level of 20 mM.

The K requirement for optimal plant growth is about 2–5% of the dry weight of the vegetative parts, fleshy fruits, and tubers (Marschner, 1986). Excess amounts of K

may also have undesirable effects: the absorption of other ions, in particular calcium and magnesium, may be impeded, and as a result deficiency symptoms may appear.

Potassium requirements depend on crop, climate, and soil conditions. Generally root and tuber crops require more K than cereals; requirements are highest during the vegetative stage; root length and number of root hairs affect the uptake potential of a crop and hence its efficiency in fertilizer use; and the better the crop is supplied with nitrogen, the greater the yield increase due to K.

Most of the soils of the dry regions are relatively rich in potassium. These large reserves are a function of soil depth, clay origin, and the degree of soil weathering, combined with limited losses by leaching. High levels of available soil potassium are generally associated with montmorillonitic and illitic clay minerals (Hagin and Tucker, 1982).

With the low yields that are usually obtained in these regions with rainfed cropping, liberation of fixed potassium from the soil has usually been able to keep pace with the removal of this element by the crop, and K deficiencies have been rare, except in sandy soils.

When irrigation is first practised on these soils, response to K fertilizers is usually meagre or non-existent. In Southern California, certain soils had been intensively cropped for over 100 years before K deficiencies occurred (Lunt et al., 1974).

Fixation of potassium

When a potassium fertilizer is added to the soil, a part of the potassium is adsorbed by the soil colloids, in more or less unavailable compounds. The part so 'fixed' is usually directly proportional to the amount of colloidal matter in the soil, being greatest in heavy soils, and least in light soils. It is assumed that the potassium ions enter into inter-layer lattice positions, where they become fixed, after displacing equivalent amounts of calcium, magnesium or sodium. The exchange occurs most readily in soils in which calcium, magnesium, or sodium, predominate – a situation that is characteristic of many arid lands.

Fixation is not generally as acute a problem for potassium as for phosphorus; it helps to reduce leaching losses and luxury consumption. Fixed potassium can be considered as a reserve supply whose availability to plants is intermediate between that of exchangeable and naturally non-exchangeable forms.

As a rule, potassium uptake is facilitated by increases in soil temperature (Miller and Army, 1954).

Potassium fertilizers

All commercial potassium fertilizers are water-soluble. The chief sources of potassium are potassium chloride (KCl) and potassium sulphate (K_2SO_4).

Potassium chloride. This salt, called commercially 'muriate of potash', contains the

equivalent of 60–63% of K_2O (according to its purity) and is the most widely used form of potassium fertilizer).

For a few specific crops, such as potatoes, tobacco, and hemp, the chloride may have undesirable effects. However, under irrigation, the amount of chlorides added by fertilizing with potassium chloride is practically insignificant in relation to the considerable amounts introduced with the irrigation water.

Potassium sulphate. This salt contains 50 to 53% of K_2O . Except for certain crops, such as tobacco, in which Cl has an adverse effect on quality, there is no essential difference between the behaviour of these two fertilizers in the soil or in their effect on crops. Under certain conditions, the accompanying sulphur may be an advantage to be taken into consideration. In general, however, the choice will depend on the relative cost of the K unit in the two fertilizers.

Potassium nitrate. This salt, which contains 44% K_2O and 13% of N, is an excellent but expensive fertilizer. Though used on a relatively restricted scale, all the world production is consumed.

Slow-release potassium fertilizer. A sulphur-coated potassium chloride has been developed, similar to sulphur-coated urea. This fertilizer may be useful for sandy soils, which have no or little potassium retention capacity (Hagin and Tucker, 1982).

Secondary nutrients

Higher yields due to irrigation, more productive varieties, and improved technology, have increased the rate of depletion of secondary and micronutrients. Another circumstance contributing to the more frequent occurrence of micronutrient deficiencies nowadays than formerly is that high-test, relatively pure fertilizers are increasingly replacing the bulkier nutrient carriers that were previously marketed, and that usually included some secondary and micronutrients as incidental impurities. A further factor in this connection is the decline in the use of farmyard manure for field crops. Finally, the replacement by mineral nitrogen, of much of the nitrogen that is symbiotically fixed by leguminous plants, has reduced the role of legumes as mobilizers of soil micronutrients that are otherwise unavailable to other plants. Deficiencies are frequent in the alkaline and calcareous soils which are prevalent in many of the dry regions, and in which the availability of boron, iron and manganese, is relatively low (Jewitt, 1966).

Calcium

Calcium is absorbed by the plant as the ion Ca^{2+} , and is in equilibrium with magnesium, potassium, sodium, and boron. Any upset of this balance has undesirable effects on vital physiological plant processes. These disturbances are not necessarily

due to a deficiency of Ca, but often to a lack of nutrient balance. The Ca content of plants varies from 0.1 to more than 5.0% of dry weight, depending on growing conditions, plant species, and plant organ. Monocotyledons have a much lower optimum Ca requirement for growth than dicotyledons (Marschner, 1986).

Calcium is the only mineral nutrient (other than, possibly, boron) which functions mainly outside the cytoplasm. It provides stable but reversible intermolecular linkages, predominantly in the cell walls, which respond to changes in micro-environment and are part of the control mechanism for growth and development. Ca is not only non-toxic at levels below 10 mM, it also effectively detoxifies high concentrations of other mineral elements (Marschner, 1986).

Under conditions of high light intensity and a high level of Ca^{2+} uptake, most of the pectic material formed is calcium pectate, which serves as a cementing material between cell walls. The proportion of calcium pectate in the cell walls is important for the ripening of fruits and influences the susceptibility of the tissues to fungal pathogens (Marschner, 1986).

Most arid and semi-arid soils are rich in Ca, which accounts for about 80% of their total exchangeable cations. The main source of Ca in these soils is calcium carbonate, which accumulates because of its low solubility. Many other primary minerals supply Ca on weathering. There is, therefore, in general no need to be concerned with its supply to crops grown in the dry zones. However, gypsum (CaSO_4) may be required in relatively large amounts in alkali soils, in order to improve the aggregation of soil colloids through the replacement of Na by Ca in the exchange complex.

Sulphur

Atmospheric SO_2 is absorbed and utilized by plant foliage, but S is taken up by the plant mainly from the soil, as the sulphate ion SO_4^{2-} , which is subsequently reduced within the plant.

The S requirement for optimum growth varies from 0.2 to 0.5% of the dry weight of plants. Requirements are lowest for Gramineae and highest for Cruciferae. Although S is not a constituent of chlorophyll, it plays an important part in chlorophyll production. Moreover, it is required for the synthesis of the amino acids cysteine and methionine, both of which are precursors of S-containing coenzymes and other plant products.

A deficiency of S inhibits protein synthesis, coincidental with an accumulation of soluble organic nitrogen and nitrate. The sulphate content of S-deficient plants is very low, and increases rapidly when the sulphate supply is sufficient for optimal growth. S is also a constituent of vitamins H (biotin) and B1 (thiamine pyrophosphate) (Marschner, 1986).

There is usually no shortage of sulphur in arid-zone soils. Many of the commercial fertilizers incidentally supply significant amounts of S; irrigation water also usually has a high content of sulphates, which in itself may be ample for crop requirements. In highly industrialized countries, SO_2 air pollution can be a major source of S;

absorbed in excess by foliage it causes direct damage to vegetation, as well as indirectly through so-called 'acid' rain.

However, S deficiencies may appear with intensive cropping, where S-carrying fertilizers are not applied (Dryland Agriculture Technical Committee, 1979). For example, S deficiency was experienced in many areas of the Sahel when use of N and P fertilizers carrying S was reduced or discontinued (Ahn, 1977).

The rates of S required are relatively low. Reductions in yields from applying excess S have not been observed, even in dry years (Dryland Agriculture Technical Committee, 1979).

Magnesium

Magnesium is absorbed by plants as the ion Mg^{2+} . Its uptake can be strongly depressed by other cations, as well as by a low pH. Magnesium deficiency can therefore result from competition with Ca^{2+} , K^+ , NH_4^+ , etc.

Magnesium is involved in the formation of chlorophyll of which it is the only mineral constituent. It also has an essential role in protein synthesis; Marschner (1986) points out that lower chlorophyll contents in Mg-deficient leaves is caused by inhibited protein synthesis, rather than a lack of Mg^{2+} per se for the synthesis of chlorophyll molecules. The most visible symptom of Mg deficiency is chlorosis of the fully expanded leaves.

Magnesium requirement for optimal plant growth is generally about 0.2 to 0.5% of the dry weight of the vegetative parts. Slight and transient deficiency symptoms during vegetative growth do not necessarily signify that yield will be depressed, unless irreversible changes occur, such as reduced grain number per ear in cereals (Forster, 1980).

Magnesium is found in the soil in the crystal structure of primary minerals or in clay minerals such as vermiculite, in which forms its availability to plants is very low. It is released by weathering as an exchangeable ion or in the soil solution. Soils of the dry zones are generally not deficient in magnesium, which accounts for about 5% of the soils' exchange capacity. However, following the introduction of irrigation, Mg deficiencies may appear, in particular on sandy soils (Hagin and Tucker, 1982).

Magnesium sulphate is the most commonly used fertilizer. It can be applied directly to the soil, or in irrigation water. Soaking of seeds in a 2% magnesium sulphate solution was found to stimulate seed germination in a number of crops, such as maize, sugar beets and several pulses. Kiss (1979) attributed this effect to an increased formation of adenine phosphate and proteins.

Sodium

Sodium is absorbed by plants as the ion Na^+ . It is not an essential element, except possibly for a limited number of crops that have been domesticated from wild plants that grew near the sea – such as sugar beets. It can replace potassium to some extent, and increase crop yields when there is a relative deficiency of the latter. There is

usually no shortage of sodium in arid-land soils, and enormous amounts are added to them by irrigation.

Micronutrients

Soils of arid and semi-arid climates generally have a low availability of micronutrient cations: zinc, copper, manganese, and iron, because of high pH, and a preponderance of calcium and magnesium in their exchange complex (Katyal et al., 1987).

Most of the micronutrients are components of some key substance in plant metabolism, or are essential to the functioning of an enzyme system. Therefore, though the quantities of the heavy metals required for normal plant growth are extremely small, as compared with the major elements, a deficiency of a micronutrient may have extremely disturbing effects on vital plant processes.

When a deficiency occurs, a very small amount of a chemical containing the micronutrient concerned may suffice to restore normal plant growth; however, an excess application of certain minor nutrients may be even more dangerous to the plant than the deficiency it was supposed to cure. For several of the micronutrients, such as iron, manganese, copper, and zinc, their concentration in the plant in relation to other heavy metals is of greater importance than the absolute amounts present (Tisdale and Nelson, 1966).

Boron

The total B content of soils is generally between 20 and 200 mg/kg, of which only 0.4 to 5 mg/kg is available to plants. A continuous supply of B is necessary for the maintenance of meristematic activity (Gupta, 1979). Dicotyledenous plants generally have a higher requirement for boron than do the monocotyledons (Gerloff, 1963).

What is known of B requirements of plants has resulted mainly from studies of the effect of B deficiencies (Marschner, 1986). One of the most rapid responses to B deficiency is the cessation of root growth, giving the roots a bushy appearance (Bohnsack and Albert, 1977).

Under conditions of severe B deficiency the protein content of young leaves decreases and the content of soluble nitrogen compounds, especially nitrate, increases (Hundt et al., 1970).

B deficiency results in a disturbed pollen-producing capacity of the anthers, as well as a reduced viability of the pollen, germination, and tube growth (Agarwala et al., 1981). This causes impaired fruit formation, and occasionally parthenogenesis. In sugar beets, B deficiency causes the disease called crown and heart rot; in many plants, it typically causes the development of scaly surfaces and the formation of internal and external cork-like material (Mengel and Kirkby, 1982). In others, the internodes are shortened, giving the plants a bushy or rosette appearance (Marschner, 1986).

Deficiencies of boron are generally rare in arid soils. However, when such deficien-

cies do occur, they can be remedied by the application of borax to the soil at rates of 5 to 10 kg/ha. B becomes rapidly fixed when applied to an alkaline soil; therefore borax has to be applied annually in small dressings, to B-sensitive crops, such as lucerne, sugar beets and cotton, when they are grown on B-deficient soils (Cook and Davis, 1957). Alternatively, boric acid can be used for foliar sprays.

Boron toxicity assumes great practical importance in dry regions when farmers irrigate for long periods with water having a high boron content. The critical B content in irrigation water varies from 1 mg/l B for sensitive crops to 10 mg/l B for tolerant crops (Marschner, 1986).

Iron

Iron is present in all soils, in quantities that are far in excess of plant requirements, but the content of soluble Fe is very low in comparison with the total Fe present. In the leaves, the critical level of iron varies from 50 to 150 mg/kg dry weight. Any problem of iron supply is therefore most frequently one of limited availability.

Iron is absorbed from the soil in ionic form (mainly Fe^{2+}) or as Fe chelates. Plant species vary in their ability to take up inorganic Fe^{2+} which has a low solubility. Fe-efficient plants are able to lower the pH of the nutrient medium and to increase the reducing capacity of the root surface under Fe-stress conditions, and thereby improve Fe availability considerably (Marschner, 1986).

Poorly aerated, waterlogged soils and soils with a high water table are conducive to a reduction of Fe^{3+} to Fe^{2+} by anaerobic bacteria, causing an increase in solubility of iron. In paddy soils, the concentration of soluble Fe may reach toxic levels, causing a disorder of the leaves in rice called 'bronzing' (Mengel and Kirkby, 1982).

Iron is involved in the activation of a number of enzyme systems, and a continuous supply is necessary for the production of chlorophyll.

Iron is a constituent of hemoproteins and Fe-S proteins (Sandmann and Boeger, 1983), as well as a number of less well characterized enzymes in which Fe has an important role.

A major role of Fe is in the biosynthesis of chlorophyll, and the most visible symptom of Fe deficiency is chlorosis, which typically always begins in the younger leaves (Mengel and Kirkby, 1982). In the roots of many plant species (with the exception of cereals), Fe deficiency causes morphological changes: inhibition of elongation, increased diameter of the apical root zones, and abundant root hairs (Marschner, 1986).

Chlorosis is the typical symptom of Fe deficiency in plants; this does not necessarily indicate an insufficiency of this nutrient in the soil, but reflects the inability of the plant to absorb soil Fe, which happens most frequently on calcareous and alkaline soils.

The lime-induced chlorosis is due to a physiological disorder caused by excess carbonate, which causes Fe immobilization in the plant (Mengel and Kirkby, 1982).

For the treatment of chlorosis, iron chelates are used, applied either to the soil or as a foliar spray.

Copper

This metallic element is absorbed by plants in very small quantities as the cupric ion Cu^{2+} . Cu content of most plants is generally between 2 and 20 mg/kg in dry weight of the plant and is mainly concentrated in the leaf chloroplasts. It is possible that Cu is involved in the synthesis of chlorophyll. It functions as an enzyme in reduction and oxidation systems of the plant, is involved in the activation of several enzymes, and possibly also in the light reactions of the plant. Its salts are apt to be poisonous at higher concentrations, and some are used as fungicides. The most rapid response to Cu poisoning is the inhibition of root growth (Wainwright and Woolhouse, 1975).

The Cu content of most soils is very low, but a deficiency leading to crop problems is extremely rare (Mulder, 1950).

Crops differ in their sensitivity to Cu deficiency: oats, wheat, and lucerne are among the most susceptible. A typical trait of Cu deficiency in cereals is a bushy appearance and leaves with white twisted tips. The application of 1–10 kg/ha Cu, as copper sulphate, to Cu-deficient soils is generally sufficient to overcome the problem (Mengel and Kirkby, 1982).

Manganese

This metallic element is absorbed by the plant as the ion Mn^{2+} . It is relatively immobile and tends to concentrate in the leaves of the plant.

The biochemical functions of Mn resemble those of Mg and it can replace the latter in many reactions. Mn is involved in photosynthetic CO_2 evolution (Marschner, 1986); it functions in the activation of a number of important enzymes, and plant growth is frequently impaired by a deficiency or excess of Mn.

As occurs with Mg, a deficiency of Mn causes interveinal chlorosis; however, in the case of manganese, deficiency symptoms are first visible on the younger leaves. In cereals, greenish grey spots appear on the more basal leaves (speck disease). The critical Mn level in most plant species is 10–20 mg/kg in the dry matter of mature leaves (Marschner, 1986).

Manganese availability depends on soil pH, organic matter content, microbial activity and soil moisture (Mengel and Kirkby, 1982). Soluble Mn decreases a hundredfold for each unit increase in pH (Lindsay, 1972). Under very dry conditions Mn salts in the soil can be irreversibly dehydrated, and thereby become less available. Double salts may however be split by drying, which releases Mn^{2+} (Mengel and Kirkby, 1982). By contrast, in waterlogged acidic soils, such as in paddy fields, the anaerobic conditions increase Mn availability, and may even result in Mn toxicity. This is not the case with calcareous or sodic soils (Mengel and Kirkby, 1982).

Most soils contain adequate levels of available Mn, but for the reasons outlined

above, deficiencies occur quite frequently on calcareous and alkaline soils, as well as sandy soils.

Zinc

Zinc is absorbed by plants as the ion Zn^{2+} . It plays a role in the production or destruction of a number of auxins; a deficiency of Zn causes imbalance in the auxins of the plant. It is an activator of a number of enzymes, in particular the activities of various enzymes of the CO_2 assimilation pathway; as a result, zinc deficiency is related to an impairment of carbohydrate metabolism and a drastic reduction in protein synthesis and protein content (Marschner, 1986).

Critical deficiency levels are below 15–20 mg Zn per kg dry weight of leaves. Deficiency symptoms in dicots are stunted growth (rosetting), and a marked decrease in leaf size (little leaf), often associated with chlorosis. In the monocots, chlorotic bands appear along the midrib, and a red, spot-like discolouration of the leaves occurs frequently (Rahimi and Bussler, 1979). Grain yield is relatively more depressed than total dry-matter production (Marschner, 1986).

Crops differ in their susceptibility to Zn deficiencies; e.g., maize will show a marked Zn deficiency under conditions in which lucerne is able to grow normally (Arnon, 1958).

Large applications of P fertilizers to soils low in available Zn may induce Zn deficiency. When this occurs, Warnock (1970) found that Zn-stressed maize plants accumulated high levels of Fe and Mn, contributing to the adverse effects of Zn stress. There is also a high correlation between available Zn and soil organic matter (Follett and Lindsay, 1970).

In most soils, the total Zn content far exceeds crop requirement and availability is the main limiting factor (Mengel and Kirkby, 1982).

Deficiencies in Zn may appear on alkaline soils, on calcareous soils, and on those which are excessively rich in P. Such deficiencies frequently occur in California in patches, in fields that have been levelled for irrigation, whereby the organic-rich surface soil has been removed (Brown and Krantz, 1960).

Zn deficiency can be overcome by spraying a crop with a 5 g/kg solution of zinc sulphate, or, alternatively, by applying zinc sulphate to the soil, at a rate of about 4 kg/ha Zn, which is effective for 3 to 8 years (Mengel and Kirkby, 1982). Zinc chelates can also be used. They have the advantage that chelated zinc applied to calcareous soils remains soluble and available to plants for much longer than the inorganic form (Iyengar and Deb, 1978).

Molybdenum

Mo is absorbed as molybdate by plants. Plants contain less than 1 mg/kg by dry weight. Mo is an essential component of two major enzymes in plants: nitrogenase and nitrate reductase.

MoO_4^{2+} is required only in minute quantities, but deficiencies have been reported for a number of crops, especially legumes – first in Australia and subsequently in many parts of the world (Berger and Pratt, 1963). It is required for *Rhizobia* for dinitrogen fixation and by non-legumes for nitrate reduction (Tisdale and Nelson, 1966), and is therefore important in protein synthesis.

Mo can be applied by soaking seeds, before sowing, in a solution of sodium molybdate.

Chloride

This halide element is absorbed by the plant as Cl^- . For many years it was not considered as essential for plants; this view is no longer accepted (Johnson et al., 1957). The physiological requirement is very low, and most plants contain levels of Cl much higher than required, generally in the range of 2–20 mg Cl per g dry matter. In the halophytes, concentrations are far higher (Mengel and Kirkby, 1982).

The Cl content of arid soils is usually high, because of limited leaching and a high salt content. The problem is therefore rarely one of Cl deficiency, but, on the contrary, of direct or indirect damage to crops through its excess, which can be very detrimental to a number of plants.

Plants species differ in their sensitivity to Cl: sugar beet, barley, maize, tomatoes are highly tolerant; tobacco, beans, potatoes, some legumes are very susceptible. For the latter, sulphate-based fertilizers are preferable to chloride carriers (Mengel and Kirkby, 1982).

Kafkafi et al. (1982) have shown that increasing the chloride concentration in the nutrient solution reduced nitrate uptake by the plant.

Cobalt

This metallic element is essential for plants that rely on dinitrogen fixation, as it is involved in the formation of the haemoglobin needed for the process (cf. p. 487). In Australia, Co deficiencies occur on fairly extensive areas.

Determining fertilizer requirements

Diagnostic methods, which would make it possible to advise the farmer on the kinds and amounts of fertilizers to apply to each crop under the specific conditions of each farm, are of considerable economic importance, and even more so since the steep increase in costs following the oil crisis of the 1970's. The problems involved have been under study for many years, and a number of approaches have been developed.

Diagnosis of estimated nutrient requirements involves at least four stepwise investigations; soil and plant chemical analysis (including biological tests), annual agronomic experiments, long-term experiments and modelling (Burford, 1987).

Soil tests

Problems

The use of soil analyses to predict a plant's response to fertilizers is based on the correlation between some fraction of a nutrient extracted from a representative soil sample and a measured response from fertilizer applications. Soil-analyses–fertilizer-response relationships, except for $\text{NO}_3\text{ N}$, are generally based on an analysis of 'plough-layer' soil samples. This procedure has generally given a reliable basis for predicting a response, *provided that adequate and up-to-date field calibration data are available* (Jackson et al., 1983).

There is no difficulty in determining the soil's content of essential elements by chemical methods. However, it is not the amounts of nutrients present in the soil that are of significance to crop production, but their availability in the proper proportions throughout the growth of the plant. This is a function not only of the soil but also of the crop, its environment, and management. It is therefore not surprising that no chemical tests have yet been devised that are able to provide an accurate assessment of the amounts of essential elements which are available to the plant in the soil, and hence the amounts that need to be added. In spite of these difficulties, by correlating the results of soil tests with the crop responses obtained in fertilizer experiments in the field, it has been possible to develop analytical methods which make it possible to predict *approximate* fertilizer needs. These tests are, however, empirical, and appropriate only to the specific soil types for which they were developed. Their interpretation requires calibration with fertilizer field experiments, and their reliability depends on the practical experience of the interpreter. Most of the original tests have been developed for the acidic soils of the humid temperate regions and are not suitable for arid-region soils with their tendency to alkalinity. Much of the work has, therefore, to be repeated in arid regions.

There also arise numerous practical problems of sampling, analysis, and interpretation. Applying the results of soil tests is further complicated by the fact that the availability of soil nutrients is not the same for all crops; different crops are also able to obtain their nutrients from different soil depths. Accordingly, the interpretation of the chemical tests will be different for different crops (and even for varieties of the same crop), and will vary according to their places in the crop rotation. Nitrogen availability in particular is influenced by complex edaphic, climatic, and biotic factors that frequently make a chemical soil test meaningless.

A rise in temperature of the soil may speed up nitrification and thereby release relatively large amounts of nitrogen; leaching and denitrification, on the other hand, may cause rapid losses of nitrates. Tests for potential nitrogen availability have been developed, but these methods have been adopted to only a very limited extent.

Reliability

From the foregoing it is clear that soil analysis cannot provide absolutely reliable

data. Mengel and Kirkby (1982) conclude that the relative lack in reliability “in no way belittles the importance of soil testing”. They point out that the data provide a relative indication of soil fertility status that, if carried out over several years, will provide valuable information on whether the fertilizer practice adopted is maintaining, improving or decreasing the level of available nutrients.

Determining rates of N fertilizer

The determination of the most economical rate of N fertilizer to apply, is based on two separate criteria: (a) an estimate of the amount of N fertilizer required for highest economic yield, and (b) the amounts of available N that can be released to the crop.

The fertilizer rate is calculated by subtracting the N-supplying capacity of the soil from the total quantity of N required by the estimated crop yield.

N requirement for highest economic yield

The first component for making decisions on the rate of N to apply for nonleguminous crops is a yield goal on which to base the total N requirement. The amount of N required for different yield levels of major crops is well known, so that once a yield goal is defined, the decision on the fertilizer rate is simple.

In semi-arid environments, in view of the erratic nature of precipitation, decisions on yield goals are far from simple. Tucker (1988) describes the problem faced by the farmer. The yield goal must be logical and realistic. If the yield goal is too high, and is not achieved, more N will be applied than is needed, and in view of the mobile nature of N, will be lost before the next crop is planted. If the yield goal is too conservative, potential high yields in favourable seasons cannot be attained.

Tucker (1988) points out that no fool-proof, objective method for setting a realistic yield goal has as yet evolved. Using average yields as a criterium in semi-arid areas is too conservative, and has been shown to lower average yields over the years.

The following rules of thumb are suggested as possible guidelines in deciding on yield goals (Tucker, 1988):

- highest yield within the past 5 years, under good crop management;
- long-term average $\times 1.5$;
- yields of top growers in the vicinity, on the same kind of soil.

Tests for available nitrogen

Tests for potential N availability have been developed, notwithstanding the limitations described above. One such method (Fox and Piekielek, 1978) is based on the measurement of the amounts of nitrate present in the root zone of the crop to be sown. The amount of nitrate is correlated to the probability of fertilizer response (determined by local experiments). Nitrogen fertilizer rates are then based on this estimate.

Other methods are based on the potential of soil organic matter to release N during

the growth period of the crop. Many researchers have shown that there is a good relation between mineralizable N in the soil and the response to N fertilizer applied. The mineralizable fraction of organic reserves is determined by incubating the soil under standard temperature, moisture and aeration conditions, and the nitrates generated over a standard period are measured (Stanford and Hanway, 1955).

Using this method, good correlations between the measurements of potential nitrates and the response to N fertilizers were obtained in several experiments (Hagin and Shmueli, 1960; Hagin and Halevy, 1961).

These methods are appropriate under semi-arid climatic conditions and controlled irrigation, when nitrate leaching below the root zone is prevented (Hagin and Tucker, 1982).

Chemical methods, that are faster than the incubation methods, have also been developed, based on many research reports showing that the mineralizable fraction of organic nitrogen is similar in a large number of soils. Most of these methods measure ammonium N or total N in acid or alkaline soil extractions, after boiling or autoclaving in water or dilute salt extractions. One such method is based on an acid and oxidative (H_2SO_4 , KMnO_4) soil extraction (Stanford and Smith, 1978).

Determining rates of P fertilizers

Determining the most economical rate of P fertilizer to apply cannot be based on probable yield levels, because of the immobility of this nutrient, and must therefore depend on soil test values.

Efforts to develop methods to measure the total forms of P available to a crop during a season have failed (Tucker, 1988).

Methods for estimating available P

Many methods have been developed for testing soils for available P. All of them involve the treatment of soil samples with a suitable extractant that removes an accessible nutrient fraction. These include the extraction of P from soil by different techniques: water, sodium bicarbonate solution (Olsen), various combinations of acids, anion exchange resin, radioactive isotope, and others. For details of these methods the reader is referred to Kafkafi (1979).

Tucker (1988) rightly stresses that "soil test interpretations and fertilizer recommendations based on one region with one set of soil conditions may not be valid for another region. The varying soil chemical properties in semi-arid regions makes calibration for a single extractant for P difficult".

Most of these tests were developed for neutral and acid soils of the temperate regions. The most widely used method for the calcareous, neutral, and slightly basic soils prevalent in the dry regions is the one developed by Olsen et al. (1954). Numerous experiments in many countries have shown a good correlation between the crop response to P fertilizers and P extracted by the Olsen method.

However, critical values below which no response to P fertilizers should be ex-

pected vary widely, according to soils, crops, and management techniques (Hagin and Tucker, 1982) and must therefore be calibrated in each case (Kafkafi et al., 1968). Field experiments (cf. p. 535) are needed to establish critical levels for different environmental conditions and to determine the relationship between the soil test value and yields to levels of added P.

The capacity of a soil to replenish the level of P in the soil solution in response to uptake by plants is more important than the quantity available at any given time. Therefore, soil tests must be calibrated with appropriate field experiments (Tucker, 1988). Using these data, and taking into account the nature of the crop, the physical conditions of the soil, the management of the preceding crops and their residues, together with cultivation methods, moisture régime, etc., an experienced diagnostician may be able to predict the probability of profitable crop response to fertilizers, and the approximate amounts of them that should be applied (Fig. 11.3).

On the basis of the soil tests, the soils are classified into from three to five levels in relation to phosphorus and potassium availability (Fig. 11.4). The accuracy of the tests does not generally justify more than three levels: *low*, at which an application of about double the amount of nutrients removed by each cropping is recommended in order to allow for some build-up in the soil in addition to the immediate crop requirement; *medium*, at which the amount recommended is slightly higher than that removed for phosphorus, and slightly lower than that removed for potassium; *high*, at which less than the rate of removal is recommended (Nelson and Stanford, 1958).

Olsen et al. (1954) give a scale according to which 0–5 mg P per kg is low; 5–10 mg P per kg is medium, and above 10 mg P per kg is high.

Determining K fertilizer requirements

The rate at which plants grown under intensive management take up potassium is more rapid than the rate of release from non-exchangeable sites; therefore, for practi-

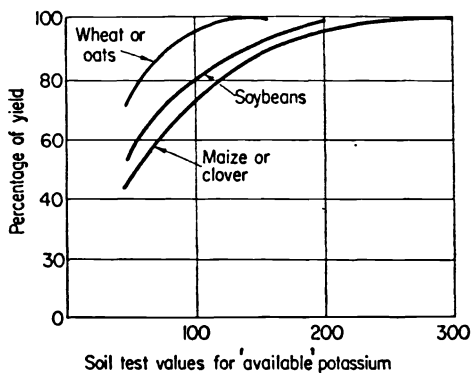


Fig. 11.3. Relationship between percentage of yields without added K for different crops and soil test values for available K (where yield with adequate is 100%). From Viets and Hanway (1957). By courtesy of the US Department of Agriculture.

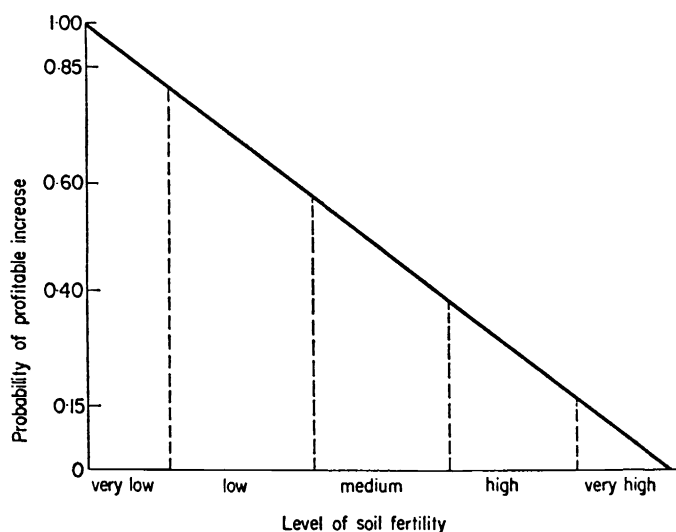


Fig. 11.4. Effect of level of fertility on the probability of obtaining a profitable response from a given nutrient. From Fitts (1955). By permission of the American Potash and Phosphate Institute.

cal reasons, only the exchangeable K at the time of sowing is considered as an immediate source of K supply to the crop (Feigenbaum and Kafafi, 1972).

The determination of K fertilizer requirements follows the same rules described for P, as K is also an immobile nutrient. The same procedures in defining yield goals and using soil test values are applicable (Figs. 11.3 and 11.4).

Evaluation of plant-available potassium

A number of methods have been developed for this purpose: measurement of K concentration in the soil solution or of exchangeable potassium, extraction with ammonium acetate, sodium bicarbonate, or mineral acids; determining the exchange energy of K with the prevalent divalent cations, and others. Many of the methods are not suitable for the soils prevalent in the dry regions, and none have given consistently a good correlation with the response to K fertilization under varying conditions of soils, crops, and climate.

In India and in Israel, the measurement of exchange energy as described by Woodruff (1955) has given the most reliable results. In Israel, it is the routine method in extension service laboratories (Halevi, 1977).

Differences in clay content and different types of minerals present in the soil can effect critical K soil test values because these soil properties affect K supply (Jackson et al., 1983).

Nemeth (1985) describes a method for soil testing, based on the use of different electrical field strengths and temperatures in an aqueous soil suspension, called elec-

tro-ultrafiltration (EUF), by which different soil nutrient fractions may be obtained. This method makes it possible to distinguish between nutrient intensity (soil solution concentration) and nutrient quantity (exchangeable and easily soluble nutrients). EUF provides more information on the rate of replenishment of P and K than do the conventional chemical extraction methods. EUF can also serve as an indicator of the readily soluble, organically bound N pool that can contribute to the N supply in the following growing season.

Fertilizer field experiments

Importance

Field experiments, that are carried out according to certain rules which ensure that a valid statistical analysis of the results can be made, are still the most satisfactory method for ascertaining crop response to fertilizers in a given environment, and are also essential for calibrating the soil tests mentioned above.

Annual experiments are needed for two main reasons: (a) to provide a check on soil and plant tests, and (b) to provide preliminary information on the rate of nutrients needed (as these are not usually predicted from chemical tests) and on the consistency of responses between years (Burford, 1987).

Long-term field experiments

The main drawback of annual field experiments is that, since the nutrient level in the soil is not static, the results obtained reflect a one-time situation, that is not likely to be repeated in time or space.

They also “suffer from the laxity of the connection between cause and effect that is their unavoidable characteristic” (Fitter and Hay, 1987).

Long-term experiments are needed (a) to determine variability between seasons; (b) to determine the residual and long-term effects of fertilizer applications on soil nutrient status; and (c) to provide input information for mathematical models (ibid.).

In brief, it is essential to continue to carry out field experiments, even if they are time-consuming and expensive, and not always conclusive.

Procedures

A satisfactory soil test calibration research programme should include a large number of field experiments encompassing soils differing as much as possible in their content of the available nutrient to be tested.

Tucker (1988) lists the required procedures for fertilizer field tests:

- the experimental design should conform with requirements for valid statistical analysis;
- adequate amounts of all nutrients, excepting the one tested, should be applied;
- the tested nutrient should be applied at several rates, either in an arithmetical or in a geometrical progression;

- a quantitative integration on soil test value and yield responses is calculated;
- a suitable model is chosen.

Mathematical models

Modelling can provide a useful basis for predicting nutrient inputs needed to maintain a desired soil nutrient status at benchmark locations, and also for predicting nutrient needs throughout an area from results at a few benchmark locations (Burford, 1987).

Mathematical models have been developed that integrate information obtained from soil tests (available nutrients) and from field experiments (response to fertilizers) in order to obtain an estimate of fertilizer requirements for specific situations.

“The quantitative description of the effects of fertilizers on yields, the calculation of optimal rates, development of soil test calibration equations, analysis of variance from fertilizer experiments, all require the representation of yield as a function of available nutrients in the soil. A suitable mathematical model is chosen, and values for its parameters estimated by some maximum-likelihood statistical procedure” (Hagin and Tucker, 1982).

The Mitscherlich equation

The earliest and best known model is the Mitscherlich equation. Modern mathematical techniques have confirmed the legitimacy of this early technique, based on the *law of the minimum*, formulated by Sprengel at the beginning of the 19th century and subsequently applied by J. von Liebig to problems of crop production.

This equation, as well as certain modifications that have been made, are based upon a general mathematical expression of the law of diminishing returns, whereby, because “as a growth factor is increased to improve yields, the yield increments become smaller”, a relationship is expressed in an asymptotic response curve (Mengel and Kirkby, 1982) (Fig. 11.5) and in mathematical terms by the equation

$$\frac{dy}{dx} = k (A - y),$$

where y =yield, x =growth factor, A =maximum yield, and k = a constant.

For a detailed description of the Mitscherlich equation and its application to fertilizer use the reader is referred to Mengel and Kirkby (1982).

The Mitscherlich equation is used throughout the world for determining which, if any, growth factor is limiting under a given set of environmental conditions. It is applicable in the practical range of soil conditions and rates of application of fertilizers. It is mainly used for P and K.

For the lowest end of the yield curve, on soils very deficient in a given nutrient, the first increments do not result in a steep increase in yield, as expected from the Mitscherlich model, probably because of fixation by the soil. It is only after the absorp-

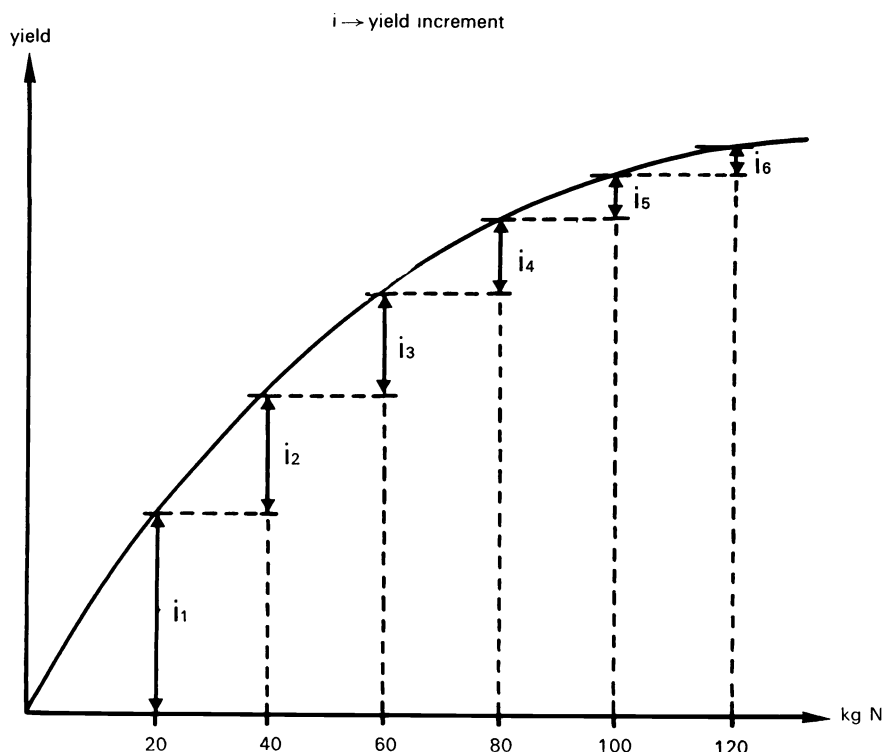


Fig. 11.5. Mitscherlich response curve showing diminishing increments. From Mengel and Kirkby (1982). By permission of the International Potash Institute.

tion and fixing sites are saturated that a marked response is obtained. Hence, the sigmoid shaped curve that is obtained.

Excessive applications of fertilizers may depress yields, and this is not accounted for in the Mitscherlich equation (Hagin and Tucker, 1982).

Computer simulation models

In summing up the papers relating to soil fertility assessment and management, presented at the International Conference on Dryland Farming, the Rapporteur (Westfall, 1988) concludes that: "The inability to make fertilizer recommendations that ensure maximum economic return under diverse rainfall conditions is a major factor that limits production. Better climatic predictive models need to be used in conjunction with fertilizer recommendation models in order to ensure maximum economic return to fertilizer investment".

A computer model can be used with relative ease to develop more comprehensive and dynamic models of the nutrient status of the soil, taking into account changes in

nutrient availability in the course of the growing season, due to changes in soil and climatic conditions.

A model that relates nitrogen requirements to available moisture, using data derived from field experiments, soil tests, and meteorological statistics was prepared by USDA scientists for wheat production in the Western states.

Models for predicting nutrient availability and nutrient uptake under field conditions must be based on both soil and plant parameters, with root parameters as the key element. One such model was developed for Israeli conditions by Kafkafi et al. (1978), on the basic assumption that nutritional stress should be prevented during growth, and therefore an optimum concentration of nutrients in the soil solution should be maintained throughout the uptake period.

The main plant parameters considered are the uptake rate of nutrients during the growing season, depth of root penetration, and sensitivity to ammonium. The model calculates, at preset time intervals, the balance between the quantity of nutrients in the root zone and uptake by plants. A decision has to be made on the kind and amount of fertilizer to be applied if the deviation from the optimum exceeds a predetermined value.

Summing up

The methods for diagnosing fertilizer requirements by soil tests calibrated by the results of field experiments and interpreted by experienced workers, are still not perfect tools. In a critical review of the subject, Kafkafi (1979) states:

- All response equations in present use have a major drawback, as they do not contain physiological parameters derived from theory, but use empirical parameters that fit the experimental results only.
- Continuing with the ‘yield response equations approach’, would entail an endless repetition of routine fertilizer experiments.
- No simple model will reflect reality accurately.

Kafkafi concludes that “in order to progress to the final goal of predicting the fertilizer requirements of crops grown on various soils in various climates, one must study and understand all the main processes that occur along the way from treatment application to the final yield”. Models should therefore not be used as a hypothesis to be verified, but rather as a starting point for changes that will be introduced as the result of the experimental observations.

Biological tests

A number of biological tests have been developed for diagnosing fertilizer requirements by using higher plants, soil fungi, or microbes, as indicators. One method consists of growing a suitable indicator plant in the greenhouse, in pots containing a relatively small amount of the soil to be tested. The plants exhaust the soil rapidly,

nutrient deficiencies being thereby revealed. Analyzing the plants after harvesting, or comparing the growth of the indicator plants in containers that have received various combinations of nutrients, with the unfertilized control, make possible conclusions regarding the fertilizer requirements of the soil that is being tested. Another approach is to prepare a number of cultures from the soil to be tested, inoculate them with the appropriate micro-organism – such as *Azotobacter*, *Aspergillus niger*, etc. – and then study the response of the micro-organisms to the soil, with and without added phosphorus and potassium.

The biological methods give a better indication of the general availability of plant nutrients than do chemical soil tests, but have the same drawbacks in that they cannot take into account individual crop response, the physical condition of the soil, environmental conditions, etc.

Plant tissue tests

As the plant itself is an integrator of all the factors affecting nutrient availability, it has long been thought that an analysis of plant tissue should reflect accurately the nutrient status of the soil.

At first the ash of the entire plant was analyzed, but it was found that there were many cases in which no correlation could be established between the amounts of the essential elements in the ash and the response of the crop to fertilizers. Subsequently, it was found that analyzing the tissue of a metabolically active part of the plant, such as a fresh leaf, gave a generally accurate estimate of the nutrient status of the plant at the time of testing – provided it was not growing under conditions of acute deficiency. When there is a severe deficiency of one or more nutrients, growth is stunted and the plant tissues may show a higher *concentration* of the nutrient(s) than those of a plant growing under more favourable conditions.

The tissue tests give rapid and fairly accurate results. Chemical analyses of plant tissues provide a basis for quantitative evaluation of deficiencies, toxicities, and imbalances in nutrient supplies (Jackson et al., 1983). The interpretation of leaf analysis is based on the assumption that, when the concentration of a certain element in the tissues of the plant is below a certain *critical* level, the uptake of that element from the soil is insufficient.

Critical levels are not fixed concentrations of a nutrient in the tissues, but a range of values. Critical levels are usually defined as those levels at which growth or yield is 5 to 10% below maximum (Bouma, 1983).

Critical nutrient levels established for plant samples are relatively constant over a wide range of climatic conditions for a specific crop. Therefore, foliar analysis can be used over a wider range of conditions than soil test values (Dryland Agriculture Technical Committee, 1979).

The *protein content* of grain crops is a reliable indicator of soil level in available nitrogen towards the end of the growing period. The first increments of available soil N are used by the plants to produce yield, and only additional N, above the require-

ments for this purpose are used for increasing protein content. Hence, a higher than usual protein content indicates that N fertilizer supply has been more than adequate (Hagin and Tucker, 1982).

Disadvantages. The main disadvantage of tissue tests is that the results are obtained at a time when it is too late to correct a deficiency of phosphorus or potassium for the current crop, though a top-dressing with nitrogen might still be feasible. Plant tissue tests are therefore mainly used for perennial crops and for high-value crops such as cotton and sugar beets, to reveal nitrogen deficiencies. With cotton, excellent correlations were obtained in 90-day-old plants between nitrogen, phosphorus, potassium, calcium and magnesium levels in the leafstalks and the amounts of these elements available in the soil, at a time when no deficiency symptoms could be seen (Joham, 1951).

Overall, leaf or tissue tests correlate fairly well with soil tests. However, the relationship between nutrient content and nutrient availability in the soil generally follows an asymptotic curve (Fig. 11.6). Above a critical nutrient level in the plant, even marked increases in nutrient availability in the soil will be reflected by relatively small increases in plant nutrient content. From this, Mengel and Kirkby (1982) conclude that leaf or tissue analyses are useful mainly in the range of low nutrient availability, and soil analysis is more appropriate in the higher range of availability (Fig. 11.6).

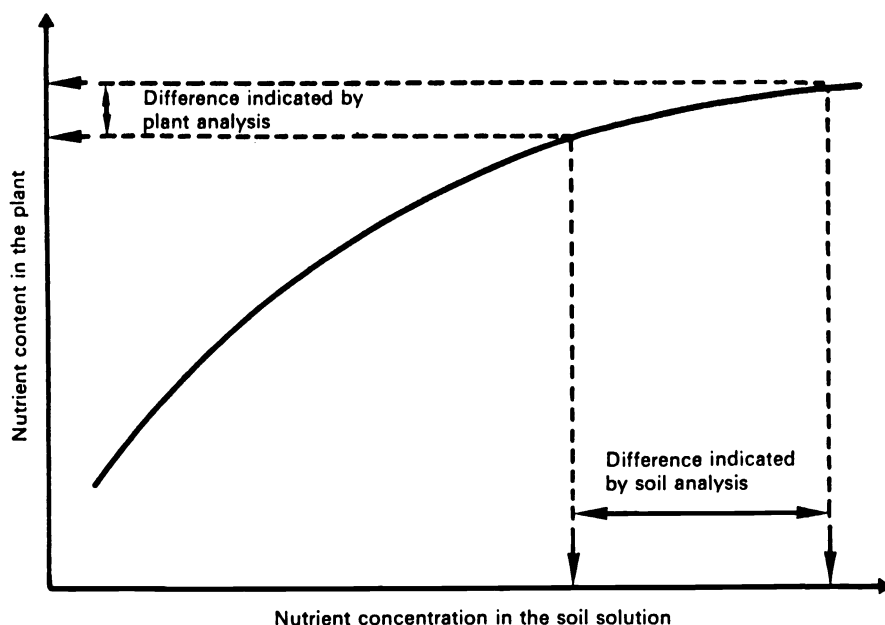


Fig. 11.6. Relationship between the nutrient content of the soil solution and the nutrient content of the plant. From Mengel and Kirkby (1982). By permission of the International Potash Institute.

Deficiency symptoms

Certain nutrient deficiencies cause characteristic symptoms to appear in the plant which make a visual diagnosis possible. The principal symptoms are severe stunting, leaf or stem discolouration, and delayed or advanced maturity.

The characteristic hunger sign for nitrogen – yellowish-green leaves – is well known. It is a familiar form of 'chlorosis'. The older leaves are the first to show these chlorotic symptoms, which spread progressively to the younger leaves of the plant. Nitrogen-deficiency symptoms may be related to a deficient water régime: the upper soil layer, which contains most of the available nitrogen, dries out rapidly between irrigations. In this case the hunger signs do not indicate a deficiency of nitrogen in the soil, but the inability of the plant to absorb nitrogen from the dry soil layer.

Phosphorus deficiency is indicated by a dark-green colour of the seedlings, and a purplish tint of the stems and leaves. The purple colouration is due to a decrease in protein synthesis as a result of P deficiency, with an attendant increase in sugar concentration in the plant tissues. Higher sugar concentrations promote the production of anthocyanin, the source of the purple colouration. However, the symptoms usually appear at a time when it is already too late to correct the situation.

A deficiency of available potassium is characterized by stunted growth, brown, necrotic leaf margins, and a tendency to 'lodge' because of a poorly developed root system. In lucerne, the leaves show characteristic white spots.

Chlorosis is, in many crops, an indication of a shortage of available magnesium or iron rather than of nitrogen.

The above are but a few examples of visual deficiency symptoms. Special coloured plates have been prepared, showing deficiency symptoms in a number of crops, such as those of Bergmann (1983).

Using deficiency symptoms as a diagnostic tool is simple and frequently effective; however, it has a number of drawbacks. Thus, the deficiency symptoms are an indication that the plant is already under severe stress, and yields may already be affected even if nutrients are applied immediately.

There are some exceptions: visible symptoms of Mg deficiency can be observed fairly often in cereals during stem extension, but these are transient and do not adversely affect grain yield (Pissarek, 1979). On the other hand, nutrient deficiencies may be insufficiently severe to cause visual symptoms. Such a level of deficiency is called 'hidden hunger' (Garrard, 1958). Moreover, the symptoms may be misleading: different nutrient deficiencies may show similar symptoms, while similar symptoms may also be caused by waterlogging, low temperatures, disease, etc.

Diagnosis can be especially difficult when more than one element is deficient, or there is a deficiency of one nutrient and another is present at a toxic level (Marschner, 1986).

Damage by excessive quantities of certain herbicides may generate physiological nutrient deficiency; the affected plants will show the identical deficiency symptoms as those resulting from a soil deficiency (Hagin and Tucker, 1982). Altogether, much

experience is needed for a correct assessment of nutrient supply based on visual symptoms.

Factors affecting the efficiency of fertilizer application

Agronomic efficiency of fertilizers is defined in two ways (Katyal et al., 1987):

- the increase in yield per amount of nutrient applied (expressed as kg of yield increase due to fertilizer per kg of fertilizer nutrient);
- the proportion of the nutrient taken up by the crop, expressed in percents of the amount applied.

Here we are concerned with efficiency in terms of yield; efficiency in terms of nutrient losses will be treated in the context of fertilizers and environment (cf. p. 427).

Soil and plant root factors

The most important soil factors in relation to nutrient supply to the roots are the nutrient concentration in the soil solution, the rate of nutrient replenishment, and the amount of readily available nutrients in the root zone (Marschner, 1986).

Soil-moisture régimes

In arid agriculture, the basic problem in plant nutrition is that of adjusting fertilizer applications to the moisture régime under which the plants are expected to grow. This is true for both rain-fed and irrigated crops. Basically, the problem is one of nutrient–soil-moisture interactions. At one end of the spectrum, under conditions of sparse rainfall, is the need to limit fertilizer application to rates which will not promote more growth than the available soil moisture can sustain until harvest – or in other words, to prevent upsetting the very delicate and critical balance between vegetative and reproductive growth under conditions of limited moisture. At the other end of the spectrum when the farmer controls the supply of water to his crops, his aim is to ensure a level of nutrient supply that will enable the plant to make full and efficient use of the favourable moisture conditions which it enjoys.

Soil moisture affects the efficiency of fertilizer use mainly in two ways: by improving the uptake of nutrients and by increasing dry-matter production. When considering the effect of soil-moisture level on the uptake of nutrients by plants, indirect effects of soil moisture must also be allowed for – such as the effects on the physiological activities of the plant, on soil aeration, and on the osmotic pressure of the soil ‘solution’.

Effect of soil moisture on nutrient uptake. Three mechanisms are involved in determining the effect of soil moisture on nutrient uptake:

(1) A favourable water supply increases the mass and distribution of the root system; actively growing roots will take up more nutrients by exploring a greater volume and depth of soil than do others. Conversely, nutrient deficiencies can restrict root development, so that uptake of water and nutrients can be impaired – especially from the lower soil levels. When soil moisture is inadequate, phosphorus uptake is impeded – probably because of reduced growth of roots towards the sources of phosphorus in the soil (Cooke, 1967).

(2) The flow of soil water transports the more soluble, and therefore mobile, nutrients to the roots (nitrates, sulphates, etc.).

(3) The less mobile nutrients, such as phosphorus and potassium, reach the plant roots partly through diffusion. As plant roots take up the nutrients in their immediate vicinity, these may be replaced by ions that diffuse slowly, from areas of higher concentrations to the depleted zone around the roots. Though the distances involved are very small, at most 5–6 mm, this is an important mechanism of nutrient supply to the roots. The diffusion occurs through the films of water surrounding the soil particles. As the soil becomes progressively drier, the water films around the soil particles become thinner, thereby reducing the rate of diffusion of nutrients to the roots.

Plant root factors in fertilizer uptake

At low moisture levels the soil water potential is much lower at the root surface than that of the bulk soil. Roots and soil particles shrink as the soil dries, causing a loss of soil–root contact (Faiz and Weatherley, 1982) which will evidently affect nutrient uptake. Hence the importance of a high root density and root length in the uptake of nutrients supplied by diffusion. For example, the higher capacity of ryegrass compared to red clover to absorb P and K is attributed to the fact that the total root length of ryegrass is fivefold that of the clover (Steffens and Mengel, 1981).

However, the relationship between root length and the uptake of nutrients supplied by diffusion is not linear; when the root density is high, the uptake rate levels off, due to the overlapping of the depletion zones of individual roots (Nye and Tinker, 1977).

For deep-rooted crops, such as lucerne, nutrient supply from the subsoil during periods of drought may make a substantial contribution to crop requirements. Fox and Lipps (1955) have shown that about 3% of the total root mass of lucerne takes up more than 60% of the total nutrients from the subsoil during drought periods.

When moisture stress is relieved, root growth is no longer impeded mechanically as in dry soil, and nutrient supply through diffusion and mass flow becomes maximal.

Soil moisture and nutrient interactions

When the water supply is deficient the stomata close, uptake of carbon dioxide is reduced, and photosynthesis decreases. Less dry matter is produced and fertilizer nutrients are less efficiently utilized than when water is plentiful. This interaction of moisture supply and nutrient supply is reciprocal.

The interrelation between soil moisture and fertilizers (or their effects on yields) has been most intensively studied. Only a few typical examples for some crops can be cited. In experiments carried out in Mexico, irrigating an improved disease-resistant variety of wheat, grown on a deep alluvial soil that was deficient in nitrogen, increased yields by only 5%, although soil moisture was maintained at the optimal level. When nitrogen was added to the driest soil, yields were increased to 3.7 times the former level, but when the same amount of nitrogen was added in combination with optimum soil-moisture conditions, yields were increased almost sevenfold (Richardson, 1960).

In Fig. 11.7, the effect of the typical interaction between nitrogen fertilization and the soil moisture régime in maize is strikingly evident and is typical of many experiments of this kind. These results were obtained in the Negev, Israel, on loess soil, with a low level of inherent fertility (Shimshi, 1966).

When irrigation water was applied without N fertilizer, the yield response to increases in the number of irrigations was relatively small; when nitrogen was applied at different rates, the response to N increased when more water was applied, up to an optimum level. This optimum increased progressively from 250 kg/ha N for 2 irrigations, up to 350 kg/ha N for 9 irrigations. In brief, two important relationships were found: (a) limited supplies of irrigation water were used efficiently with fertilizers; (b)

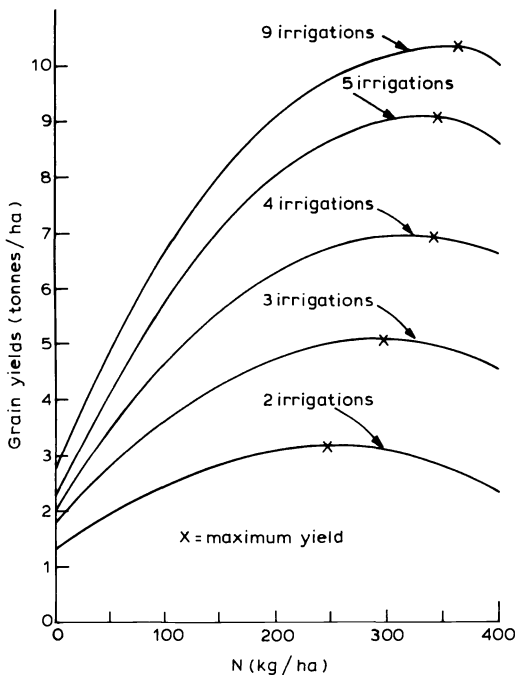


Fig. 11.7. Effect of N fertilization at different soil-moisture régimes on grain yields of maize. After Shimshi (1966). By permission of the author.

the increased supply of irrigation water was used even more efficiently. The converse is equally true, as shown in the schematic graph of Fig. 11.8.

In a more recent experiment in the same location (Shimshi and Kafkafi, 1978) the interaction between N rates and soil water supply was investigated on autumn-sown wheat (Fig. 11.9). With the introduction of high-yielding semi-dwarf wheat varieties, it was found profitable, in the drier parts of the country, to supplement the low rainfall with one or two irrigations. However, in order to achieve the potential of these productive varieties, and justify the expense incurred by irrigating, the optimum fertilizer rates, in particular of N, had to be determined.

Grain yields in this experiment ranged from 3040 kg/ha from the rain-fed (363 mm) and unfertilized treatment, to 6340 kg/ha for two irrigations plus 180 kg/ha N treatment. There was a strong interaction of irrigation and fertilizers on grain yields, mainly due to late irrigation. In the absence of late irrigation, the optimal N rate was 120 kg/ha. With late irrigation, the optimal rate was 180 kg/ha N. Higher rates (240 kg/ha N) caused a decrease in yield in all treatments. Lack of nitrogen reduced soil water extraction during the grain-filling stage, particularly from soil layers deeper than 60 cm.

On cotton, a well-defined interaction between soil moisture and fertilizers has been established (Scarsbrook et al., 1959). At low moisture levels there was no response to fertilizing with nitrogen at rates above 67 kg of N per ha. At the intermediate moisture level, there was a response to 134 kg of N per ha, and at the highest moisture treatments, cotton responded to all the levels of N tested – including 268 kg/ha. Conversely, the nitrogen applied increased the efficiency of water utilization. At the highest moisture level tested, the cotton lint produced per mm of water applied was about doubled by applying 268 kg of N per ha, as compared with 67 kg N per ha.

Stanberry et al. (1955) studied the effects of three moisture régimes and 10 rates and/or frequencies of phosphate applications on the yields of lucerne in Arizona. They found that a progressive increase in lucerne production, with added increments of P_2O_5 , occurred for each moisture treatment, and that, for a given amount of phosphate applied, yields increased as soil-moisture tension was decreased. The yield of hay over a three-year period from low-fertility, low-moisture plots was 16.1 t/ha, compared with 36.1 t/ha in high-fertility, high-moisture plots.

In Nebraska, under conditions in which moisture was *not* limiting to yields (over 600 mm of rainfall), water-use efficiency of grain crops (wheat, oats, maize, sorghum) was found to increase by an average of 29% following judicious use of fertilizers. The fertilized crop consumed only an extra 25 mm of water (Olson et al., 1964).

In other trials in Nebraska, it was found that maximum yields on low-nitrogen soils resulted from the application of 22 kg of N per ha for every 75 mm of available pre-planting moisture (Fig. 11.10) (Ramig and Rhoades, 1963).

Many more experiments of this kind have been reported in the literature, with extraordinarily consistent results, showing that nutrient and water requirements are intimately linked, and that fertilization increases the efficiency with which crops use

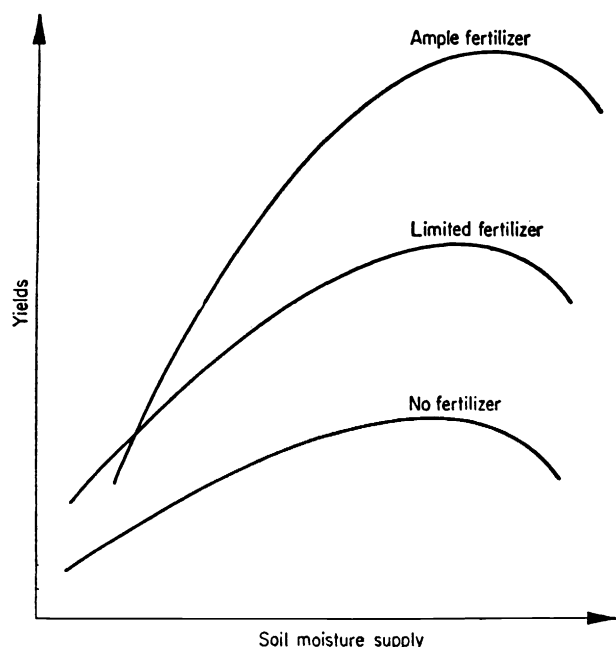


Fig. 11.8. Schematic graph showing generalized crop response to levels of fertilization in relation to soil-moisture régimes.

available water; furthermore, favourable water régimes make possible fertilizer applications at levels which would be entirely ineffective under conditions of moisture stress.

Fertilizer application under conditions of low moisture supply

The problem. A special problem arises on the fringe of the semi-arid regions in which rainfall is normally low and droughts are frequent. In these regions the effects of fertilizers under varied conditions of precipitation have not been studied as intensively as in the humid regions; many of the fertilizer experiments that have been carried out in semi-arid regions have not been sufficiently reliable for predicting crop response to fertilizers. The results of the fertilizer trials are erratic, and often fail to correlate with chemical soil tests (Power et al., 1961).

The following example gives an indication of the difficulties with which farmers and researchers are faced in deciding on fertilizer policy under these conditions. In one season, yields of wheat were increased significantly by fertilizer application in Oklahoma in seven locations out of eight; in the following season, which was much drier, a yield increase with fertilizer application was obtained in only one location out of these eight (Eck and Stewart, 1954).

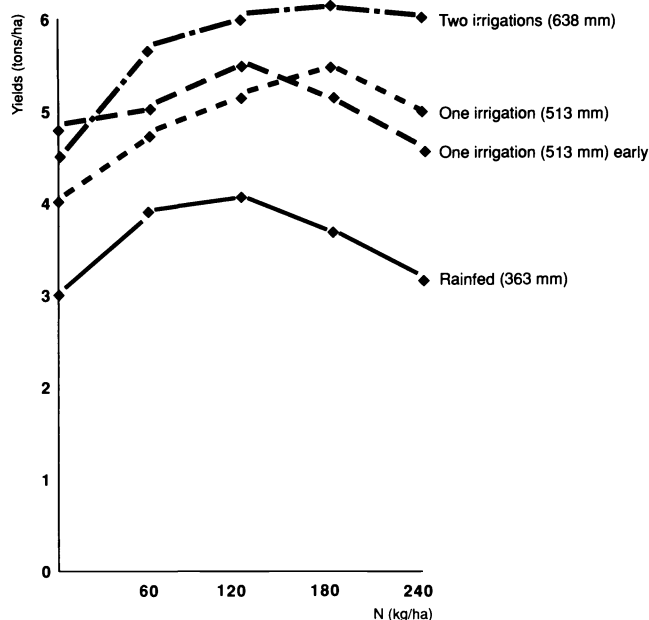


Fig. 11.9. Interaction between rates of N fertilizer application and water supply on wheat. Based on data from Shimshi and Kafkafi (1978).

When is fertilizer use justified? Under the distinctive climatic pattern of the dry regions, with their relatively limited and erratic rainfall and long drought periods, certain patterns of fertilizer use have evolved. Farmers have frequently been disappointed, under conditions of limited water supply, by crop response to fertilizers; in some cases their application was even detrimental to yields. Under such conditions, an extremely cautious fertilizer policy has evolved, even progressive farmers usually employ very limited rates of application.

In the semi-arid tropics, for example, the use of fertilizers was traditionally considered to be too risky to be economically viable. Contrary to this general belief, Viets (1967), from a review of studies on the effect of fertilizers on crop yield in drier regions, concluded that most evidence indicated that the use of fertilizers in these regions is justified and improves the efficiency with which a limited water supply is utilized by the crop. He further pointed out that yield reductions due to moderate fertilizer use are rare.

Several studies since the late 1970's have established a significant positive response to fertilizer N in semi-arid areas in India. The degree of response depended on rainfall, soil depth and native soil fertility.

A four-season study, conducted by the International Fertilizer Development Centre (IFDC) in collaboration with ICRISAT, on a Vertisol, was concluded in 1985 (Katyal et al., 1987). The aim of the study was to determine the response of rainy

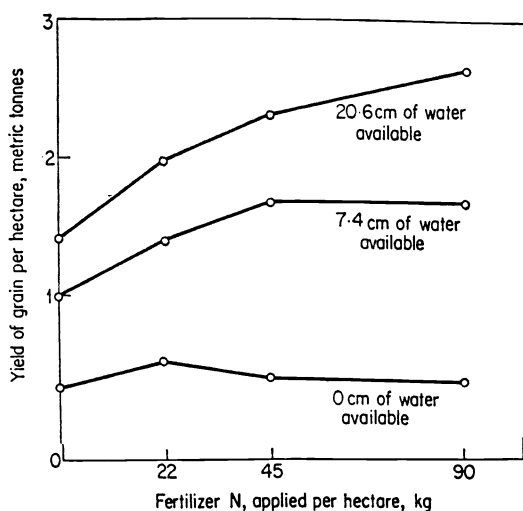


Fig. 11.10. Yield of grain of winter wheat in western Nebraska as influenced by rates of N application and the amount of available stored water at sowing time. The different quantities of water were supplied by pre-irrigation, and correspond to 0, 61, and 183 cm of soil wetted to field capacity, respectively. From Ramig and Rhoades (1963). By permission of the American Society of Agronomy, Inc.

(summer) season sorghum to urea applied at rates from 0 to 120 kg/ha N. Rainfall in the four seasons (1982–1985) ranged from 322 to 913 mm. Yield increases from fertilizer N ranged from 300 to more than 2000 kg/ha sorghum grain.

The general response was linear up to 60 kg/ha N, levelling off occurred at about 60 kg/ha N. On shallow soils, overall yields of sorghum were lower, and levelling off occurred at rates above 30 kg/ha N. On an overall basis, in this four-year study, each kg of N produced, on average, 25 kg of grain.

For Alfisols in the semi-arid tropics (summer rainfall) El-Swaify et al. (1984) recommend the following fertilizer strategy; initially, as a short-term goal, N fertilizer rates should be adjusted to seasonal rainfall as follows:

Seasonal rainfall (mm)	Rate of N (kg/ha)
Below average	40
Average	60–80
Above average	80–120

The ammoniacal form is the one preferred, applied in bands in split applications – part basal and the remainder in two or more top-dressings.

As a long-term goal, soil organic matter should be built up by the use of farmyard manure and crop residues, and wherever possible by legume–cereal sequential cropping.

Phosphorus should be applied as water-soluble P fertilizer, in bands, before sowing.

The rates should be calibrated by soil tests, as follows; with less than 5 mg/g Olsen extractable P, the application rate should be 15 kg/ha P; when the rate of extractable P is 5–10 mg/g, only 10 kg/ha P need to be applied.

Zinc should be applied once in three to four years, at a rate of 50 kg/ha ZnSO_4 .

Crops grown on stored soil moisture. In regions with a Mediterranean climate, i.e., where a summer drought alternates with a moderately cool winter-rainfall season, it is possible to grow summer crops whose entire moisture supply is provided by water stored in the soil during the rainy season. Typical crops which give fairly good yields under these conditions are sorghum, cotton, sesame, and cucurbits.

Under these conditions, crops do not usually respond to fertilizers that are applied to them directly. Although early growth may be somewhat stimulated by such application, under the conditions of limited moisture supply, this is no advantage. The lack of sustained response is probably due to the fact that the fertilizers are applied in the top soil. By the time the plants have reached a stage of development when nutrient requirements are maximal, this soil layer has completely dried out, and the nutrients contained in it are virtually ineffective. This view is supported by the fact that crops grown on stored soil moisture give very poor yields on low-fertility soils, but react favourably to a fertility build-up resulting from fertilizing preceding crops.

The situation is different when a crop that is dependent on stored water also receives a limited amount of rainfall or a supplemental irrigation during its growth period. The results of 66 trials on wheat, grown in North Dakota on non-fallow land, show that the response to fertilizers increased with increasing amounts of stored water and of rainfall occurring during the growing season. On the basis of these results, fertilizer recommendations are being made by regions, according to the probability of rainfall during the growing season, and for each region they are related to the amount of stored moisture at the time of sowing (Weiser, 1960).

The depth of soil moisture at seeding time can be determined without difficulty, and this information will therefore reduce the amount of uncertainty involved in deciding on whether to apply fertilizers, and, if this decision is in the affirmative, at what rates.

In Nebraska it is recommended to apply 25 kg/ha N for every 75 mm of available water in the 2 m soil profile (Tisdale and Nelson, 1966).

Minimum precipitation required. When soil moisture is definitely inadequate, crops may fail to respond to fertilizers, or the response may be too small to be economic. The minimum amount of rainfall needed to ensure a fairly satisfactory yield level of grain crops, which in turn makes possible an economic return on the fertilizers applied, depends on many factors, such as the efficiency of the rainfall, moisture reserves in the soil, preceding crop history, temperature, evaporation, etc. An empirical

and somewhat arbitrary figure is 300 mm of rainfall in a winter-rainfall region, combined with soil moisture reserves from fallow or else a moisture-conserving crop. Table 11.1 gives examples.

These results show clearly the effect of both rainfall and fallow on the crops' response to fertilizers. With less than 250 mm of rainfall, moisture is the only limiting factor, and less than one-third of the tests showed a response to nitrogen – and even then fertilization was not profitable. When rainfall was in excess of 300 mm, grain yields were almost always increased under continuous cropping; however, when the crops were grown after fallow, which allowed a build-up of available nitrogen, not much more than half the tests responded to fertilization, notwithstanding ample soil moisture.

In a study of the effects of rainfall and fertilizers on range production in the African Sahel, in an area with an average annual 500 mm of summer rainfall (which is considered the minimum amount of rainfall for acceptable yields in summer-rainfall regions – cf. p. 351). Breman and de Wit (1983) found that with the limited amounts of rainfall prevalent in the region, fertilizers were beneficial.

Frequently, under natural conditions, growth was found to be limited in the first part of the season by a deficiency of P, and in the second part by N deficiency. If both elements are supplied in sufficient amounts, production in the southern Sahel can increase by as much as a factor of five!

The authors come to the conclusion that low availability of N and P is a more serious problem than low rainfall.

Irrigated crops

Transition from rainfed to irrigated farming

Irrigation becomes an effective tool, for increased production maintained on a high level, only when applied in conjunction with the most intensive cultural practices, of which an appropriate fertilizer régime is one of the most important.

TABLE 11.1

Relation of rainfall and crop sequence to the response of winter grain to nitrogen fertilization (Martin and Mikkelsen, 1960)

	Percentage of tests responding to nitrogen with a seasonal rainfall of:		
	<250 mm	250–300 mm	>300 mm
Annual barley	20	46	96
Fallow barley	30	35	56
Fallow wheat	31	50	56
Average	27	44	67

With the transition from rain-fed to irrigated agriculture, it is essential that the farmers break away from the traditional fertilizer practices evolved under dryland farming, and adopt an entirely new approach that must be appropriate to the new situation.

A farmer who is accustomed to the fertilizer rates applied to rainfed crops will, at first, usually apply to irrigated crops, rates that are at best fifty to one-hundred percent higher than those which he used previously. The responses obtained from these amounts are generally so unspectacular as to create the impression that further increases of yield from fertilizer application are not to be expected. It is only when rates of applications are increased three- to fourfold or even more, that the potentialities of heavy fertilizer application for increasing the efficiency of water use are fully realized. In many crops – such as maize for grain or forage production, fodder beets, irrigated pastures, and many vegetable crops – really astonishing yield increases are obtained by heavy fertilizer dressings. The most consistently spectacular responses are obtained from nitrogenous fertilizers. Rates of up to 200 kg of N per ha for maize, 300 kg for fodder beets, and 500 kg and more for irrigated pastures, can give economic returns (Arnon, 1963).

Problem soils (Marschner, 1986)

The major soil types that pose specific nutritional problems encountered in the dry regions are alkaline and sodic soils.

Alkaline soils

Alkaline soils (cf. p. 109) are common in arid and semi-arid areas worldwide. Alkalinity (pH >7) is mainly due to high levels of calcium carbonate (calcareous soils) or of sodium carbonate (sodic soils). N is the major growth-limiting nutrient for most non-legume species. Availability of P is generally low (except in Chernozems (Mollisols)). P deficiency results mainly from low levels of total soil P and low soil moisture content.

Calcareous soils

The major nutritional constraints are due to high bicarbonate concentrations, and the main nutritional disorder when the level of CaCO_3 is >20% is lime-induced chlorosis due to a physiological inactivation of Fe, and not necessarily to a deficiency of this element. P-efficient genotypes are more susceptible to the disorder than P-inefficient genotypes. The application of organic manure to calcareous soils may be the most effective way for increasing available Fe and Zn to crop plants.

Sodic soils

In sodic soils, poor physical conditions (cf. p 112) and resultant poor aeration are the major constraints and are frequently associated with Na and B toxicity.

Saline soils

Saline soils are widespread in the dry regions when rainfall is insufficient for leaching excess salts out of the root zone and/or drainage, natural or artificial, is not adequate. Soils are defined as saline if the level of salts is sufficient to interfere with plant growth (cf. p. 110).

Salt tolerance is low for most crop species, but there is genetic variability for this trait among and within species.

The major nutritional constraints are due to (a) high osmotic pressure and resultant water stress (cf. p. 650), and (b) high concentrations of potentially toxic ions (Na^+ and Cl^-) and a high $\text{Na}^+/\text{Ca}^{2+}$ ratio.

Waterlogged or compacted soils

An expenditure of energy is required for the plant to take in ions from the external medium against a concentration gradient. This energy is provided by root respiration which, in turn, requires oxygen. Therefore, factors that impair the aeration of the soil, such as waterlogging, soil compaction, etc., will have an adverse effect on the uptake of nutrients – particularly from clay soils.

*Climate factors**Light intensity*

A very close relationship between light intensity and the response to various levels of nitrogen fertilization has been demonstrated in rice (Stansel et al., 1965). As light intensity was reduced, yields become lower at all the rates of nitrogen application that were tested. Light determined the amount of N that could be effectively used: with 100% light, all rates of N, including the highest (134 kg/ha), were effective in increasing yields. When light was reduced to 70%, yields were increased by N up to 67 kg/ha, though a higher rate of application reduced yields. With 40% light, the application of N at a low rate had no effect on yield and the heavy rate caused slightly reduced yields.

The later in the lifecycle light intensity is reduced, the larger will be the reduction in grain yield recorded. The effects of light and nitrogen were found to be similar in a number of widely divergent locations (which included California and Texas), three different varieties, and two seasons, showing that light may influence nitrogen utilization and yield over a wide range of environments (Stansel et al., 1965).

Temperature

The effect of low temperatures on nutrient uptake and supply to the shoots is primarily the result of inhibited root growth and to a far lesser degree to a direct effect on the kinetics of nutrient uptake (Mackay and Barber, 1984).

Minimum temperatures for root growth of species native to warm climates is generally between 8 and 15°C. Optimum temperatures for root growth tend to be

lower for root growth than for shoot growth, and are usually in the range of 20 to 25°C, though higher for cotton (about 30°C) (Pearson et al., 1970).

High soil temperatures have a detrimental effect on root growth, probably through insufficient carbohydrate supply to the root meristems; hormonal effects are also possibly involved (Marschner, 1986).

Plant population

The optimum number of plants per unit area depends on a number of factors, among which availability of plant nutrients is of considerable importance. When plants are widely spaced, they may be able to obtain, from the relatively large volume of soil available to the individual plant, an adequate supply of plant nutrients. However, when moisture is not limited, high yields can be achieved only at plant densities at which competition between plants for nutrients is relatively severe; an adequate supply of nutrients is therefore essential under these conditions.

Timing of fertilizer application

The proper timing of fertilizer application aims at obtaining the maximum response from the crop, by making the nutrients available at the time and rate at which they are most needed. However, the greater the number of fertilizer applications there are during the growing period, the greater will be the costs of application.

Proper timing of the fertilizer application may sometimes have an effect as great as the actual amounts applied. The need to supply phosphoric fertilizers early in the life of the plant has already been stressed. The practice of applying fertilizers in split applications – part at the time of sowing and the rest at different growth periods – has become part of accepted agricultural practice. In particular, under irrigation, and especially for N fertilizers, this practice appears to be based on sound theoretical considerations. However, many experiments on maize, cotton, sugar beets, ground-nuts, and other crops, grown under overhead irrigation, have shown no advantage whatsoever from split applications as compared with a single application prior to sowing (Arnon, 1963). This is probably due to the more complete control of water supply that is made possible by overhead irrigation, as compared with furrow irrigation or flooding. Downward movement of the fertilizers, as far as it occurs, corresponds to the development of the root system – and should be more beneficial than negative, as long as the fertilizers are not leached beyond the reach of the roots.

Another possible reason for the lack of effect of split applications could be the high rates of nitrogen applied to most crops that are grown under intensive irrigation practice. In research carried out in Nebraska with irrigated maize, it was found that the time of nitrogen application was extremely important when low rates were used, but had little effect when rates in excess of 90 kg of nitrogen per hectare were applied (Olson et al., 1960).

The whole amount of potassium required by the crop is usually given in a single application prior to, or at, the time of sowing. Losses by leaching are minimal, and even the potassium that becomes immobilized in the clay lattices of the soil is gradually released to the crop.

Phosphorus is fixed very shortly after application, and is then gradually released to the crop. Split applications are therefore hardly more effective than single, relatively heavy dressings before sowing.

Techniques of fertilizer application

The principal methods of applying fertilizers are *directly to the soil*, by broadcasting or by localized placement, *indirectly*, through irrigation water, and *directly to the plant*, by spraying on the foliage. The choice of method depends on a number of factors, such as the kind of crop and the stage of development, the characteristics of the fertilizer and the amounts required, the fixing power of the soil, the size of the area to be fertilized, and the season of the year (e.g., whether the fields are accessible to ground machinery or not).

Broadcasting

Broadcasting of fertilizers may be carried out before ploughing the land, before sowing, or on the growing crop. Broadcasting followed by ploughing makes possible an even distribution of the fertilizer throughout the ploughed layer, in which plant roots are most active. This method may be of particular importance for incorporating part of the phosphorus and potassium in soils that are deficient in these elements, as the first step in a build-up of sufficient reserves. It is also advisable when there is need for heavy rates of application which might harm the crop if they were applied in localized placement. It has been found that in alkaline soils, the thorough incorporation of the phosphorus fertilizer is of particular importance (Stanberry, 1959).

Broadcasting before sowing is used mainly for easily leached nitrogenous fertilizers, or in cases in which a light levelling of the soil follows the ploughing. The fertilizer is then disked or harrowed in. However, for summer-growing crops it may be advisable to incorporate nitrogen fertilizers at a greater depth, in a more continuously moist zone, so that the nitrogen remains available during the period between rains or irrigations when the top level of soil dries out.

Overall, and under many conditions, broadcasting will remain the most popular method of fertilizer application, because it is fast and easy, and equipment is readily available (Randall and Hoef, 1988).

Localized placement

Randall and Hoeft (1988) list four broad objectives involved in fertilizer placement: (a) ensure efficient fertilizer use by the plant; (b) prevent or reduce environmental pollution; (c) prevent fertilizer salt injury to the plant; and (d) provide an economical and convenient operation.

Efficient fertilizer use

The volume of soil that is in intimate contact with roots and root hairs usually varies between 0.1 and 5% of the whole (Wiersum, 1962), depending on the stage of development of the plant. This indicates the importance of water and nutrient movement by diffusion toward the roots, and of fertilizer placement for nutrients – especially those with low mobility, such as phosphorus. The most extensive root systems develop in soil in which plant nutrients are most abundant (Wilkinson and Ohlrogge, 1962).

In band placement, the mixing of fertilizer with soil is confined to a small soil volume, the levels of nutrients are relatively high, and the nutrients remain available for a longer time. Notwithstanding the fact that only a small fraction of the roots' surface is in contact with the banded fertilizers, the rapid proliferation of the roots in the fertilized band enables a high recovery rate of the nutrients. This is especially important in soils with a high fixation capacity.

On the other hand, when fertilizers are mixed with a greater volume of soil, a greater number of roots come in contact with the fertilizer, but more of the latter is fixed by the soil and reduced availability may result. Tandall and Hoeft (1988) conclude from the foregoing, that for maximum nutrition efficiency, a compromise must be reached between soil volume fertilized and root distribution so that the root–fertilizer contact is optimized and fixation minimized.

The efficiency of band placement also depends on the rate of fertilizer application. Band placement is generally more efficient when low to moderate rates of P and/or K are applied, especially to row crops. With higher application rates, differences in the efficiency of nutrient uptake between localized and broadcast applications diminish, especially at higher soil test levels (Randall and Hoeft, 1988).

The moisture régime also influences the degree of efficiency of band fertilization. Chaudhary and Prihar (1974) report increased yields of 48% for irrigated wheat and 288% for rainfed wheat when NPK fertilizer was banded as compared to the same amount applied broadcast. The authors concluded that in the rainfed wheat, the broadcast fertilizer remains positionally unavailable near the soil surface, due to the lack of feeding roots in that zone, which is dry most of the time.

In order to overcome this problem, Harapiak and Beaton (1986) suggest that for rainfed wheat, fertilizer P should be deep-banded and not be seed-placed. The opti-

imum depth was found to vary with locations and years, but averaged between 10 and 12.5 cm.

Reducing environmental pollution

This is a direct consequence of the more efficient uptake of the nutrients, described in the previous paragraph.

Fertilizer injury to the plants

Although the concentration of salts in the bands may exceed the accepted limits beyond which damage is normally caused to the plants, the fact that only a very small part of the root system is involved probably explains why generally no harmful effects are experienced from banding (Duncan and Ohlrogge, 1958).

Nutrient uptake of the whole plant is hardly affected when only part of its root system is in contact with high concentrations of nutrients, as a result of a compensatory increase in uptake in the favourably placed segment (Drew and Saker, 1975).

However, placing the fertilizers too close to seeds may cause a delay in germination or even reduce emergence markedly. This danger is enhanced under conditions of moisture stress. Most of the damage comes from the high salt indices of N and K fertilizers, with little effect from P fertilizers (Randall and Hoeft, 1988).

Economic and convenient operation

Numerous field experiments have shown that the most satisfactory results from banding are obtained when the fertilizer band is 5–7 cm from the seed row, and about 5 cm beneath it; this placement ensures efficient utilization of the fertilizer, and minimizes the risk of damage to the germinating seed and the seedling.

Special equipment has been devised for combined seed–fertilizer drills that can place the fertilizer band at the sides and slightly below the seed row.

Fertilizer placement for phosphorus

On soils that are very deficient in P, band fertilization will not produce maximum yields. The general level of P in the soil should first be built up by broadcast applications and incorporation in the top soil layer. Subsequent band applications will then generally be effective (Welch et al., 1966).

It has been repeatedly shown, under conditions of a favourable moisture supply, that placing water-soluble phosphates, such as superphosphate, in bands in the vicinity of the seed row, considerably reduces fixation, and enables the seedlings to develop rapidly. In arid-zone soils that are low in available P, banding may stimulate early root growth and thereby enable the plants to better resist drought conditions later in the season (Kafkafi, 1963).

Fertilizer placement for potassium

Most of what has been stated for band placement of P applies to K fertilization,

though the effects of banding are generally less marked because fixation problems are less severe for the latter. Barber et al. (1985) propose that fertilizer K should be distributed through enough soil so as to ensure that at least 10 to 20% of the roots should be in K-fertilized soil.

Fertilizer placement for nitrogen

With nitrogen fertilizers, the major concern is usually how to avoid losses, mainly by leaching; however, under dryland conditions the upper soil layer may remain dry during extended periods during which the N fertilizers applied to that layer will remain unused. Under these conditions, Chaudhary and Prihar (1974) found that when the N fertilizer was banded under the seed row, in comparison with broadcasting and mixing in the upper soil layer, higher yields were obtained.

Surface strip placing

In order to achieve a compromise between the soil volume fertilized and root distribution that optimizes root–fertilizer contact and minimizes fixation, as mentioned above, Barber (1974) proposed that P and K fertilizers should be applied on the soil surface, in 7–10 cm wide strips, at intervals of 70–75 cm, before fall ploughing. This would ensure that the fertilizers were mixed with 10–20% of the soil. In this method, a greater proportion of the root system comes in contact with the fertilizers, but less fixation occurs than with broadcasting.

Conclusions

When soil tests are low, soil moisture or precipitation is limiting, and reduced tillage is used, localized placement in bands will generally give long-term maximum fertilizer efficiency and economic return. However, a combination of banding and broadcast application is generally advisable (Randall and Hoeft, 1988).

In an intensive, well-fertilized agricultural production system, the main emphasis should be on keeping an adequate level of plant nutrients in the active root zone, rather than localized placement.

Applying fertilizers in irrigation water (fertigation)

Advantages

Applying fertilizers in irrigation water is very attractive to the farmer as it makes for economy in labour, savings in equipment, and faster crop responses at the most appropriate times. By fertigation, nutrients can be applied in synchronization with plant needs, which are different at different periods of growth. Its application depends on the type of soil, the method of irrigation used and the kind of fertilizer available.

Soil types

Coarse-textured, sandy soils are the most suitable for fertigation, and lend them-

selves well to small applications of fertilizers at suitable intervals, as is feasible with fertigation. Because of the high permeability of these soils, conventional methods of application usually result in significant nutrient losses by leaching. The possibility of controlling the leaching by fertigation may save 25–30% of the applied nitrogen (Caldwell et al., 1977). On heavier soils, by contrast, there is less danger of losses by leaching under careful irrigation management, and the advantages of split application of fertilizers are less evident.

Methods of irrigation

With surface methods of irrigation, the water distribution over the field is generally not uniform; fertilizer application in solution will further aggravate the negative results of faulty irrigation techniques.

Sprinkler and drip irrigation give a more uniform distribution of water, and uneven application of the fertilizers is minimized.

When overhead irrigation is used, the fertilizer solution should be added to the water at the beginning of the irrigation period; it is then, subsequently, washed off the plants by clear water, and damage to the plant tissues is thereby avoided.

Kinds of fertilizers

A very careful choice of nutrient carriers to be used in fertigation is essential, in order to avoid clogging the irrigation system or corrosion of its components. Therefore, the fertilizers must be water-soluble and not react with the irrigation water. Many N and K fertilizers are easily applied through drip irrigation. By contrast, the usual phosphate fertilizers may form insoluble precipitates with Ca^{2+} and Mg^{2+} in irrigation water and cause clogging (Mikkelsen, 1989). Therefore, the pH must be maintained low enough to prevent precipitation of relatively insoluble P salts; for this reason acidic P carriers are recommended, such as orthophosphoric acid, which may even eliminate clogging in the irrigation system (O'Neill et al., 1979). Some of the soluble salts of the orthophosphoric acid, such as ammonium orthophosphate can also be used.

Ammonia injected directly into water with high levels of calcium and magnesium salts, causes precipitation because of increased water pH and lowered solubility of the dissolved materials (Murphy et al., 1979). Where sprinkler irrigation or drip systems are used, calcium precipitation can clog the nozzles or emitters. With sprinkler irrigation, losses by volatilization are also considerable (Hagin and Tucker, 1982).

Potassium use in fertigation is relatively problem-free if the dosage is carefully controlled. Potassium chloride and potassium nitrate are preferred to the less soluble potassium sulphate, which in calcium-rich waters forms a calcium sulphate salt which may cause clogging (Hagin and Tucker, 1982).

The more mobile the nutrient, the greater the advantage of fertigation. With nutrient elements that are strongly fixed, such as P on fine-textured soils, sprinkler-applied

phosphate did not move below 4–5 cm, whereas in a loamy sand it moved to a depth of approximately 18 cm (Hergert and Reuss, 1976).

Equipment

Special metering devices are available for applying the desired rate of fertilizer. The simplest method is to introduce the fertilizers into the irrigation system through a fertilizer tank, in which the fertilizers are dissolved. The tank is connected through a by-pass to the irrigation line; a pressure difference of about 0.2 atm between in- and out-let causes water to move through the tank, displacing the fertilizer solution (Hagin and Tucker, 1982). An alternative method is to inject the fertilizer directly into the water stream, from a closed vessel which has a higher pressure than the water pressure in the irrigation system. The pump can be activated by the flowing water itself, with no need for an external source of energy. Another method is based on the Venturi principle: a part narrower than the main water line is inserted into the flow pass, changing the water flow velocity and pressure. The vacuum thereby created sucks the fertilizer solution from the open tank (Hagin and Tucker, 1982).

Foliar application of fertilizers

Experiments have shown that phosphorus, nitrogen, and potassium, in solution, when sprayed on the foliage, are easily absorbed and spread rapidly to all parts of the plant. Spraying fertilizer solutions directly on the foliage of a crop has the advantage of avoiding the problems of fixation, loss of availability, and losses by leaching, which occur when fertilizers are applied to the soil.

The main drawback of this method is that, in order to apply a major nutrient in a quantity which can have a significant effect on the crop, a large amount of dilute solution is needed – more than the foliage is capable of absorbing – while increasing the concentration of the solution causes scorching of the foliage and damages the crop. The other alternative is to spray a dilute solution frequently, but this will make fertilizing labour-consuming and costly.

These limitations do not apply to micronutrients. Deficiencies of iron, manganese and zinc are frequent in alkaline soils, and are not necessarily due to an absence of these elements in the soil, but rather to the chemical reactions which make them unavailable to the plant. Applying these minor nutrients to the soil therefore does not usually relieve the deficiency, whereas spraying directly on the foliage is usually highly effective.

Fertilizing the subsoil

Deep placement of fertilizer can improve plant growth and yield under drought conditions when the water potential of the surface soil decreases, provided water is available in the subsoil (Garwood and Williams, 1967).

In irrigation farming the upper 15–20 cm of the soil are periodically dried out during the intervals between irrigations. It is evident that nutrients, normally applied in the upper horizon of the soil, will pass through similar cycles of periodical unavailability. Thus, water applications not only improve the moisture status of the soil layer in which the most active and abundant roots are usually found, but also make available nutrients that had become positionally unavailable to plants.

Deeper placement of fertilizers in irrigation farming has the advantage of avoiding these periodical cycles of availability and unavailability of nutrients due to soil dryness.

Subsoil moisture plays an important role in irrigation farming through serving as a steady source of water supply, thereby offsetting the moisture fluctuations of the top soil. It is good irrigation practice to wet to its full depth, even prior to sowing, the whole soil horizon which will eventually be penetrated by the root system. This practice will, however, be ineffective if conditions are not favourable for the penetration of roots into the subsoil. Experience has shown that simply improving the physical conditions of the subsoil – even the breaking up of impervious layers between soil and subsoil – is not sufficient, though it may be noted that adequate soil fertility may enable plants to overcome compact layers.

Fertility levels are, on the whole, lower in subsoils than in surface soils – especially as regards readily available nutrients.

Gliemerth (1953) has shown that the fertility of the subsoil may greatly affect the utilization of subsoil water. He found that subsoil fertilization doubled the proportion of roots occurring in the soil layer at a depth of 36–54 cm as compared with more shallow fertilization.

These results have been confirmed by other workers, Kohnke and Bertrand (1956) found that maize roots did not penetrate deeply into a compacted silty clay-loam, mainly because of lack of oxygen (cf. p. 681). Subsoiling alone improved root development under these conditions, but fertilization of the subsoil gave even more striking results.

The adage that the livelihood of farmers is derived from the 18–20 cm of top soil is certainly not justified in irrigation farming; the full possibilities of subsoil fertilization have not yet been developed in practice, or even thoroughly investigated.

However, it can be safely concluded that whilst keeping the entire soil profile moist is good farming practice, this will not be fully effective unless a proper moisture–fertility balance is maintained.

Interactions between nutrient elements

The statement is commonplace that a balanced supply of nutrients is essential for optimum production, yet it is unfortunately true that this is not always reflected in

agricultural practice. Especially in irrigation agriculture, the high fertilizer rates that are normally used to ensure high yields, increase the likelihood of creating an imbalance. It is also a moot question as to whether a balance among only the three main macronutrients – N, P and K – is adequate.

“Plant growth is a function of two variables; of nutrition intensity and balance” (Shear et al., 1946). Not only is maximum yield dependent on optimum intensity occurring in combination with a proper balance of all the nutrients, but the effect, on yield and quality characteristics, of changing the level of supply of one or more nutrients, will clearly depend on the amount of imbalance created in relation to other essential elements. In many cases, the minimum amount of a nutrient for normal growth is not an absolute value, but depends on the relative amounts of certain other elements that are available.

The physiological effects of the macronutrients cannot be considered in isolation from one another. If there is a shortage of potassium, carbohydrate production is limited; as a result of N deficiency, only part of the organic acids in the plant can be built into amino-acids and proteins; phosphorus has an essential role in the intermediary stages of plant metabolism. Therefore, the concentration of a nutrient in the soil, in relation to certain others, may have a greater influence on plant growth than the absolute amounts available at a given time.

Irrigation farming is characterized by the high rates of fertilizers that are applied, especially in the case of nitrogen. However, the high nitrogen rates needed for high yields frequently have adverse effects on certain quality characteristics. In many cases, adequate supplies of potassium may counteract, at least partly, the adverse effects on quality of high N levels.

Plant nutrients may either aid or compete with one another for entry into the plant, and improve or impair their respective availability; e.g., high levels of N nutrition may affect K intake adversely. Ehrendorfer (1958) found that when N application was increased threefold, the K content of the plant was reduced by half. Various indirect effects, due to reducing the K content below a certain level, as a result of heavy applications of nitrogen, may therefore be exercised on various physiological processes.

The uptake of fertilizer phosphorus by wheat and oats was found to be stimulated up to twofold by nitrogen fertilization; this was attributed to the stimulating effect of nitrogen on root activity (Olson and Dreier, 1956).

K fertilization at very high levels may cause an imbalance in the supply of other essential nutrients, thereby indirectly causing some physiological deficiencies in plants. As the cation content of a plant is generally almost constant, an excessive increase in K supply will reduce uptake of Ca and Mg (Barker and Bradfield, 1963), and an adequate potassium supply will limit sodium uptake. When irrigation water high in magnesium was used, it was found that poor growth of plants resulted from a decreased uptake of potassium (Ignatieff and Page, 1958).

The uptake of zinc from the soil is improved by the use of ammonium sulphate;

sodium nitrate, on the other hand, causes a decrease in zinc uptake. This differential response has been ascribed to the effect of the nitrogenous fertilizers on soil pH.

Boron improves the absorption of calcium; phosphorus improves the absorption of molybdenum. Excessive concentrations of phosphorus may cause a deficiency of zinc; high levels of calcium may indirectly cause chlorosis as a result of iron deficiency, whilst heavy potassium rates may improve iron availability.

The balance between nutrients may be quite satisfactory at a given level of yields, yet prove inadequate when a higher yield level is made possible; e.g. by irrigation. This is a frequent occurrence with potassium in arid lands.

Residual effects of fertilizers

The higher the rates of fertilizers applied, the more important becomes the problem of residual effects of these fertilizers. These effects may be beneficial or detrimental.

The residual effect of a fertilizer may be due to one or more of the following factors: (a) the amount applied to the crop was in excess of its actual requirements; (b) slow release of a nutrient from a partly soluble carrier; and (c) part of the added nutrient was fixed by the soil or combined by microbial activity into organic forms from which they are slowly released (Beckett, 1971).

In soils in which the penetration of roots is not impeded by high acidity, compact horizons, bedrock or other unfavourable conditions, water and nutrients must be considered as accessible to crop roots down to depths of at least 150–180 cm (Herron et al., 1968). Consequently, any soluble nutrients, such as nitrates, mineralized from the soil organic matter or remaining as residues from applied fertilizers, should not be considered as lost for crop use as long as they remain within this zone.

Nitrogen

Because of the extreme mobility of the nitrogen applied in fertilizers, and the potential loss by leaching beyond the root zone, moderate rates of N fertilizer applications generally have little direct residual effects. Indirectly, because nitrogen significantly increases biomass, the release of nitrogen from crop residues may contribute a significant amount of this element to the following crops.

Phosphorus

It has already been pointed out, that due to fixation, only a fraction of P fertilizer is utilized by the crop to which it is applied; the residue becomes part of the soil reserves of this nutrient. Once an optimum level of P in the soil is achieved, crops no longer respond directly to additional P fertilizer, and only starter or maintenance dressings of phosphorus are generally required. The length of time required to reach this stage

will depend on the initial level of P in the soil and the amounts of fertilizer applied annually.

Additional effects of fertilizers on crop plants

Plant composition

Proteins

The vital role of proteins in human nutrition, and the disastrous effects on human health of an inadequate balance between proteins and carbohydrates in the diet, are well known. Accordingly, the possibility of increasing, by the judicious use of fertilizers, the absolute and relative amounts of proteins produced, is of major importance – especially for those populations whose low standard of living makes them dependent largely on plant proteins.

One of the most frequently observed effects of N fertilizers is on the protein content of cereal grains (Jackson et al., 1983). In addition to increasing yield and protein content of wheat, baking qualities were also improved (McGuire et al., 1974).

The first increments of added N generally give the largest yield increase, whilst the effect on protein is limited. As the yield increments per unit of applied N become smaller, the increments in protein increase.

The overall picture that emerges from a considerable volume of research is that only after plants have used available nitrogen required for growth processes conducive to maximum yield, do fairly large doses of nitrogenous fertilizers increase protein content (Fernandez and Laird, 1959). These authors noted that there is first a drop in protein content when nitrogen is applied at a relatively low level; this is due to the steep increase in yield which causes a ‘dilution effect’. It is only after the basic requirements of nitrogen have been met, that protein content increases with increased nitrogen. This increase is usually accompanied by a reduced biological value* of the protein which is not, however, sufficient to offset the advantage of increased protein production.

Intensive protein synthesis requires, in addition to fairly high levels of nitrogen, a balanced supply of potassium and phosphorus. The general effect of potassium, except when it is supplied at excessively high levels, is to increase the effectiveness of nitrogen and, in conjunction with phosphorus, to counteract the unfavourable effect of high N fertilization on the quality of the protein.

Figure 11.11 illustrates the occasionally conflicting effects of nitrogen fertilizer application on economic yield. Whilst the overall yield of sugar beets is markedly

**Biological value*: the degree to which the protein is able to replace ‘body protein’ that has been degraded in the course of functioning of the organism.

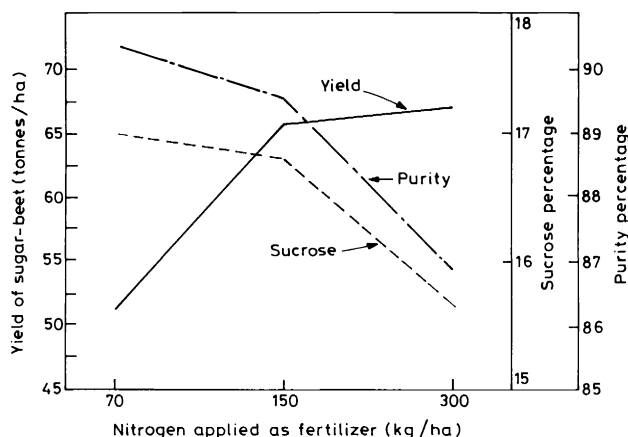


Fig. 11.11. Yield and quality of sugar beet, as affected by fertilizer application. From Haddock et al. (1959). By permission of the American Society of Beet Technologists. (Purity=the percentage ratio of sugar to total solids).

increased by N fertilization, there is a marked decrease in sucrose content and purity of the juice. The lower purity further reduces the amount of sugar that can be extracted in the processing of the beets.

Nitrate accumulation in plant tissues.

Under conditions of limited soil-moisture supply and low atmospheric humidity, the plant may take up more nitrate than it requires, as a result of the high concentration of the soil solution and its high rate of transpiration. The plant is generally not adversely affected by the excess nitrogen, but it may be harmful and even lethal to farm animals that eat forage with a high nitrate content.

Unbalanced nutrition resulting from high rates of nitrogen application under conditions of P deficiency, is also conducive to excessive nitrate accumulation in the plant tissues.

Carbohydrates and lipids. An adequate supply of potassium is essential for condensing sugar into starch, but relatively high applications of potassium as well as of nitrogen, reduce the starch concentration in the edible parts of the plant, as a dilution effect.

The effect of fertilizers on sugar content has not been found to be consistent, probably because of the transitional nature of sugars in the metabolism of the plant.

Potassium was found to have a beneficial effect on the oil content of fruits and seeds, possibly because of its role in balancing the carbohydrate–nitrogen relationships in plants.

Mineral content

The mineral constituents of foods can vary considerably, both in quantity and in their proportions to one another.

Many factors, of which fertilizers are the most important, control the uptake of minerals by plants. The observed differences in mineral content of various parts of the plant are not always understood (Lawton and Cook, 1954). When nutritive elements are applied to a low-fertility soil, the percentages of the respective elements in the plant tend to increase until a complete, well-balanced treatment is achieved. Subsequently, the more luxuriant growth generally causes a reduction, through dilution, in the levels of these elements.

The potassium content of plants is more directly influenced by the potassium content of the soil solution than is the case with other elements, because it is not converted into organic substances in the manner of most of the others.

K content of the seed of most crops is usually far less affected by K fertilization than is that of the vegetative parts. Stems of maize and wheat may contain three times as much potassium as the grain (Stubblefield and De Turk, 1940), and variations of K content under the influence of manuring are far more evident in the stems than in the grain.

Phosphorus fertilization

Whilst there is a considerable body of research on the effect of phosphorus fertilizers on the mineral composition of forage crops, in which an increase of P content as a result of P fertilization has been conclusively demonstrated (Nehring, 1965), much less work on this subject has been carried out on foodcrops. However, here too, there is a general tendency for phosphorus applications to result in an increase in P content of the produce. This was found to be true in cereals (Wenzel, 1957), in which the major proportion of the phosphorus is in the form of phytin and only a small amount is present in the inorganic form.

Climate and soil fertility may mask the effect of phosphoric fertilizers, and heavy nitrogen applications, in conjunction with phosphorus, may reduce the P content of the crop as a result of dilution due to increased growth.

However, results for P content are not always consistent (Jenne et al., 1958), probably as a result of differences in the fixing power for P of different soils, as conditioned by the soil-moisture content. This is borne out by the fact that when oats received P fertilizers, no reduction in P content was experienced under conditions of a moisture stress which induced a decrease in P content in the control plots (Bourget and Carson, 1962).

Effect of fertilizers on root development

Any influence on root development by fertilizers has relevance to the water relationships of the plant (Fig. 11.12). As water movement in unsaturated soils is both limited

and slow, an extensive proliferation of roots is essential to enable the plant to utilize soil moisture effectively. The extent of the root system also determines the depth of the reservoir from which plants can absorb water, and hence their ability to make use of water that is stored in the subsoil.

A high soil fertility is usually conducive to the proliferation of the root system; penetration in depth is frequently limited as a result of an unsatisfactory nutrient status underneath the ploughed layer.

Fox and Lipps (1955) showed that, for lucerne, a favourable nutrient régime is even more important than a favourable physical environment, for the deep rooting of the plant and for satisfactory nodulation.

Fehrenbacher and Rust (1956) reported that, in a well-fertilized rotation, maize roots penetrated to a depth considerably greater than in unfertilized controls.

Fertilizers were found to increase the root development of grasses, which resulted in more efficient extraction of soil moisture at high tensions and at greater depths (Smika et al., 1965).

It is well known that heavy nitrogen fertilization tends to increase the top-root ratio, as under these conditions only a small quantity of carbohydrates is translocated to the roots. However, nitrogen does not always have this effect, and Kmoch et al. (1957), working with wheat grown on four moisture levels and at three nitrogen rates, found that the added nitrogen increased root weights at all moisture levels and at nearly all soil depths, thereby permitting more effective utilization of the soil moisture. In all probability the problem is one of nutrient balance (Duncan and Ohlrogge, 1958).

The effect of potassium fertilizers on low-potassium soils, of decreasing the lodging of maize due to weakness of the root system is well known. Hoffer and Krantz (1949) have shown that, as a result of potassium deficiency, iron accumulates at the nodes

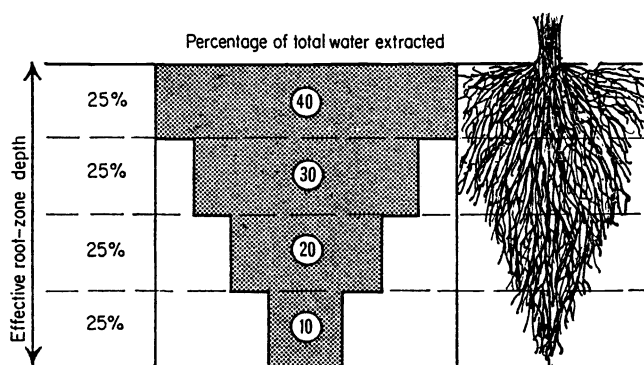


Fig. 11.12. Effect of fertilizers on the root system. The top quarter of the root zone is the first to be exhausted of available moisture. Adequate fertilization helps the plant to develop a deeper root system, and enables it to use moisture from the lower root zone, a factor of considerable importance in rainfed semi-arid cropping. By courtesy of the US Department of Agriculture.

of the stalk, thereby interfering with the translocation of nutrients to the roots; the roots become weakened and susceptible to root-rots – hence the subsequent lodging.

The application of phosphorus fertilizers frequently favours the development of the root system in various crops and may thereby increase the ratio of roots to shoots.

Maturity

A delay in attaining maturity of the crop may have considerable economic significance to the farmer. In rainfed cereal crops it may prevent the grain from ripening fully before the available soil moisture is exhausted, so resulting in shrivelled grain. In an irrigated crop such as cotton, harvesting difficulties and impaired quality of the lint may result from a delaying of maturity until after the early rains.

It is frequently stated that nitrogen fertilizers cause a delay in the attainment of maturity of most crops. Actually, if there has been a deficiency in available nitrogen, an adequate supply of this nutrient can advance maturity of wheat by as much as two weeks. Similar results were obtained with maize (Pesek et al., 1955). Properly balanced nitrogen applications, given at the right time and in the right amounts, will generally advance maturity, rather than otherwise. It is the heavy applications of nitrogen, out of balance with the supply of other major nutrients, that delay maturity.

It is well known that phosphorus helps to hasten maturity in most crops, and in particular to offset the opposite tendency of heavy nitrogen applications to delay maturity.

Fertilizers in relation to disease and pest incidence

The nutrient status of a crop may have a considerable effect on the ability of the plants to withstand disease, and the resistance of undernourished plants to disease may be considerably weakened. The high fertilizer rates associated with irrigation are bound to affect the reaction of cultivated plants to disease and insects, and may even help to control one particular disease while encouraging another.

Usually, a balanced nutrient supply that is optimal for plant growth and development is also considered as optimal for plant disease resistance. However, pathogens have nutritional requirements of their own; the interactions between plants and pathogens are therefore very complex, and cannot be resolved by such an oversimplified approach.

Palti (1981) defines the two most important nutrient practices in relation to disease resistance of plants as follows: (a) to avoid strains that may lower the resistance of crops to facultative parasites; (b) to manipulate nutrient supply to the relative disadvantage to the pathogen, either directly or indirectly.

The role of fertilizers in these complex plant–pathogen and plant–insect interactions will be treated in more detail in Ch. 18 and Ch. 19.

Effect of fertilizers on osmotic pressure of soil solution

Growth of many crops is inversely proportional to the osmotic pressure of the soil solution between the limits of 2 and approximately 10 atm (Wadleigh and Ayers, 1945), because water becomes progressively less available to plants as the osmotic pressure of the soil solution increases.

In humid regions, fertilizers will rarely have a markedly adverse effect on crop growth as a result of an increase in the osmotic pressure of the soil solution. However, the situation is different in dry regions; as the soil dries, the osmotic pressure of the soil solution increases, and will in time reach a level that adversely affects plant growth. This effect is felt sooner, the higher the concentration of salts in the solution. Soluble salts from fertilizers may accumulate, especially in semi-arid climates in which low rainfall and high evapotranspiration are the rule. Even under irrigation, moisture levels fluctuate from high to low between irrigations, and an increase in osmotic pressure of the soil, resulting from the heavy applications of fertilizers characteristic of irrigation agriculture, may have a detrimental effect on crop production, if periods of severe moisture stress are allowed to occur.

The foregoing is no reason for renouncing the benefits of fertilizer application, but further underlines the need for adjusting fertilizer supply to the moisture régime of the soil.

Plants require adequate levels of nutrition even under saline soil conditions. However, fertilizers may also increase the osmotic pressure of the soil solution, compounding the effects of salinity. It is therefore important to choose fertilizers that have little effect on osmotic pressure in the soil solution.

Fertilizers differ considerably in this respect. High-analysis fertilizers generally have a lower salt-index* per unit of plant nutrients than do lower-analysis fertilizers. For example, the salt index per unit of N for three representative N carriers is shown in Table 11.2.

In brief, low-analysis potassium and inorganic nitrogen carriers will generally cause the greatest increase in osmotic pressure of the soil solution, whilst phosphate carriers, urea, and ammonia, have relatively little effect in this respect (Rader et al., 1943).

Kafkafi (1984) suggests that salinity reduces the amount of N transported to the meristemic growing points at the top and coined the term 'induced deficiency'.

Fertilizers and non-renewable energy

Fertilizers account for nearly 70% of the total energy requirements of agriculture in the LDC's, as compared to only 35% in the developed countries, see Table 11.3.

*Salt index: ratio of increase in osmotic pressure produced by a fertilizer, in relation to that produced by the same weight of sodium nitrate based on a relative value of 100.

TABLE 11.2

Salt index of three nitrogen carriers

	Salt index	In %
Sodium nitrate	6.060	100
Ammonium sulphate	3.253	53.6
Anhydrous ammonia	0.572	9.4

At least 90% of the world supply of fertilizer nitrogen is derived from the fixation of atmospheric nitrogen with hydrogen as anhydrous ammonia (NH_3) (Blouin, 1974). In ammonia plants operated on natural gas, about one-half of the gas is used to provide hydrogen, which combines with nitrogen from the air to produce ammonia. Phosphorus and potash, on the other hand, are derived from mineral deposits, and hence fuel is required only for conversion of the raw materials into commercial fertilizers (Bakker-Arkema et al., 1974).

About five times more fuel is required to produce a kilogram of ammonia than to produce a kilogram of phosphorous fertilizer and eight times more than for a kilogram of potash fertilizer. As a result, with the exception of legumes, nitrogen fertilizers account for 70 to 90% of the total energy input of fertilizers (Hutter, 1976). When ammonia is converted into ammonium nitrate, sulphate of ammonia, urea, etc., still more fuel is needed and the discrepancy with other major plant nutrients is still greater. The direct application of liquid ammonia is therefore the most economical method, both in money and energy cost, of supplying nitrogen to the crops. However, it requires special equipment for its application, but its adoption instead of sulphate of ammonia, urea or other solid fertilizer can result in a significant saving in energy costs.

TABLE 11.3

Non-renewable energy requirements for agricultural inputs (in % of total requirements). Based on data from FAO (1981)

	Western Europe and USA	Eastern Europe and USSR	Developing countries	World
Mechanization	62	45	22	51
Fertilizers	35	52	68	45
Irrigation	1	1	8	2
Plant protection	2	2	2	2
Total	100	100	100	100

Fertilizers and the environment

This topic is addressed in Ch. 9.

Economics of fertilizer use

Determining the most economic combination and rate of fertilizers to use is the most important application of the results of fertilizer research. This requires taking into account two sets of factors – agronomic and economic.

Two types of information are needed from the agronomic point of view for making fertilizer recommendations for specific producing conditions: (a) the general yield equation for the crop, with yield expressed as a function of applied fertilizer variables and the productivity factors; and (b) the productivity levels for the specific conditions for which a fertilizer recommendation is to be made.

The amounts of fertilizer that a farmer should use does not depend only on the anticipated yield response under specific producing conditions, but must take into account a number of economic factors, such as the ratio between the cost of the fertilizer and the probable price of the product, the availability of cash on the cost of credit, the degree of risk and uncertainty involved, and the ability of the farmer to absorb these risks; conditions of land tenure, etc.

Law of diminishing returns

Applying fertilizers to crops is generally one of the easiest and most profitable ways of eliminating an important limiting factor in crop production. However, the fertilizer rates that give the highest yields are not necessarily the most profitable ones (Fig.

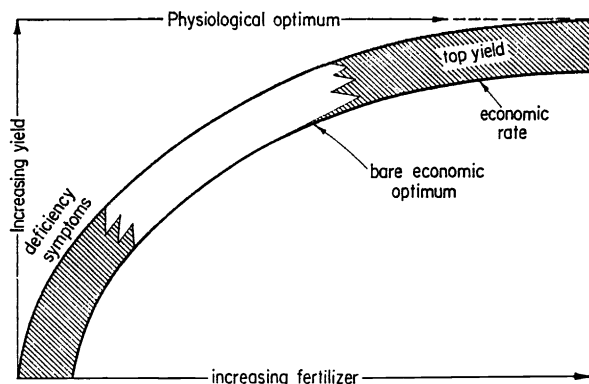


Fig. 11.13. Physiological optimum and economic optimum rates of fertilizer application. After Garrard (1958). By permission of the American Potash and Phosphate Institute.

11.13). The response to increasing amounts of fertilizer follows the law of diminishing returns, and a point is invariably reached at which an increment of fertilizer will increase costs more than it does returns. Where a nutrient deficiency is severe, the first units of nutrient added may cause a very small yield response; with additional increments the rate of response increases until an inflection point is reached; this is followed by a maximum after which yields decrease with additional fertilizer increments. In this case the overall yield response curve is sigmoid-shaped.

Determining optimum economic rates of fertilization

Many methods have been devised to analyze the results of fertilizer experiments from the point of view of maximum economic return.

Where the fertilizer experiments have been planned in such a way that a response curve can be drawn, the point of maximum return from the fertilizer can be determined graphically, as in Fig. 11.14.

All this appears at first sight fairly simple and straightforward; in practice, however, supplying fertilizers in the most economical way is a complicated problem, and fertilizer practice is still highly empirical.

The major problems encountered by the farmer in an economic analysis of fertilizer profitability are due to: (a) the uncertainties regarding yields and prices involved in his calculations; (b) the influence of the level of management on the profitability of fertilizer use; (c) the need to consider the residual effects of the fertilizers applied; and (d) the need for a decision that is usually not on the level of a single nutrient but is concerned with the most profitable combination of nutrients.

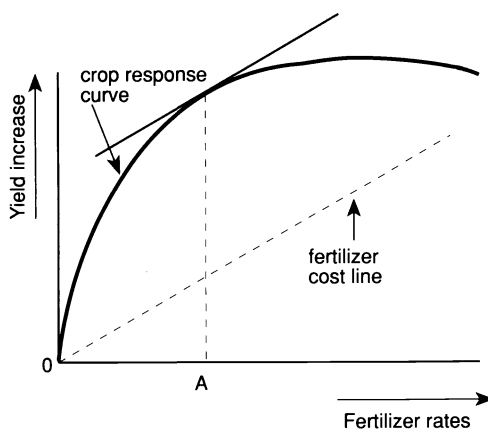


Fig. 11.14. Generalized crop response curve with associated fertilizer cost lines shown in terms of the quantity of crop increase required to pay for the fertilizer. Maximum total profit occurs at point A, where returns minus fertilizer costs are highest.

Breeding for nutrient efficiency

The meaning of nutrient efficiency

Graham (1984) defines nutrient efficiency for a given genotype as “the ability to produce a high yield in a soil that is limiting in one or more mineral nutrients for a standard genotype”. This definition can be applied to comparisons between genotypes within a species or between plant species (Marschner, 1986).

Breeding for nutrient efficiency consists in the “selection and breeding of genotypes adapted to low nutrient availability in soils, and with a high efficiency in the utilisation of soil and fertilizer nutrients” (Barrow, 1978).

The ability to produce a reasonable yield under conditions of mineral stress and problem soils should not be confused with *fertilizer use efficiency* (FUE), which is the relative productivity of different genotypes in utilizing fertilizer nutrients, i.e., the ratio yield/nutrient-supply. A high FUE is essentially a by-product of breeding for high yields (cf. p. 282), and is therefore not relevant in the present context.

Tolerance to nutrient deficiencies

In semi-arid regions, soil salinity and alkalinity and related nutritional problems such as Fe and Zn deficiencies are widespread (cf. Ch. 13). A considerable effort is invested in many selection and breeding programmes for tolerance to adverse nutrient soil conditions.

The heritability of tolerance to nutrient deficiencies

Not only are there considerable differences between plant species in their ability to take up nutrients from deficient soils, but there may be differences between cultivars of the same crop species in this respect. Strains and cultivars of a crop may also differ in their susceptibility to toxicity from high concentrations of certain elements (Gerloff, 1963).

In some cases, major nutritional traits are under the control of a single gene pair; in most situations complex genetic systems are involved (Graham, 1984).

Various studies indicate that differences in the root system affect the ability of plants to take up mineral nutrients from the soil. The efficiency with which a root system mobilizes mineral nutrients in the rhizosphere via exudates and acidification is partly a function of the local rooting density.

A positive correlation has been established between the uptake rate per unit root length in relation to the volume of the root cylinder (Marschner, 1986). In comparative studies of plant species of different root hair lengths, it was found that even within a given plant species, selection of genotypes with long root hairs results in a more efficient P uptake than from those with short root hairs (Caradus, 1982). The

fact that grasses compete with legumes in a mixed stand more effectively for potassium (Steffens and Mengel, 1981) is, according to Marschner (1986), probably related to some extent to the wider root hair cylinder of grasses, but certainly to total root length.

In some instances, the difference in utilization efficiency is related to differences in transport from the roots to the shoots, as shown by Lauchli (1976).

Studies have shown that responses to specific mineral stress characters are heritable (Clark, 1982). For example, studies on plant efficiencies in the use of N, P, and K have shown that tolerant and non-tolerant strains of tomatoes and snapbeans differed by 44% for N, 72% for P, and 100% for K (Gabelman, 1976; Gerloff, 1976).

When plants are subjected to nutrient deficiencies the permeability of their membranes increases, facilitating ion transport through the root symplast, and the root/shoot ratio increases. Therefore root parameters are most important in breeding for tolerance to nutrient deficiencies (Blum, 1988). Plants adapted to nutrient-deficient soils are better at taking up nutrients, making them more available to the plant, or at transporting them to the appropriate sinks in the plant. Resistant genotypes have been found to be more capable of increasing the availability of the deficient element by changing the chemical environment of the rhizosphere (Blum, 1988). For example, Fe-efficient genotypes release H^+ ions into the rhizosphere, which reduce Fe^{3+} to the more available Fe^{2+} .

Breeding programmes for tolerance and nutrient efficiency

A major effort for screening and breeding rice varieties for tolerance or efficiency under mineral stresses and adaptation to problem soils has been conducted at the International Rice Research Institute (IRRI) since 1965, and tolerant genotypes were found for each type of mineral stress. Of over 13 thousand rice genotypes tested for mineral stress in 1977, 259 showed tolerance. A similar screening programme has been initiated at IITA in Nigeria for low N, P, K, S, and Zn fertility, and marked differences in yields and visual symptoms were noted (Clark, 1982).

One of the successes in breeding for tolerance to a nutrient deficiency is the development of crop varieties tolerant of Fe deficiencies, such as the soybean variety Weber, which has good resistance to Fe deficiency chlorosis, when grown on calcareous soils.

Kannan (1981) found that two sorghum hybrids showed fewer Fe deficiency symptoms than their parents, when grown in a Fe-deficient nutrient culture.

Wheat is generally sensitive to Cu deficiency; while one variety – Gabo – fails totally when Cu supply is low, or has only a very low yield compared to that of the relatively Cu-tolerant Chinese Spring. Triticale, has a high tolerance to Cu deficiency, inherited from its rye parent, indicating that the specific mechanisms for Cu uptake in rye are genetically controlled and have been transferred to triticale (Graham et al., 1981).

Studies on the efficient uptake of nutrients have been intensified following the energy crisis of the 1970's, in view of the high cost of fertilizers, both in terms of cost and high energy requirements. Also, it has been estimated that at the present rate of increase in phosphorus fertilizer use, workable deposits of phosphorus would be exhausted in 100 years (Evans, 1983).

Genotypical differences in nutrient efficiency have been related to uptake, transport, and utilization within plants (Marschner, 1986). These differences relate equally to both tolerance under conditions of nutrient stress and to nutrient efficiency when ample amounts of nutrients are available.

Practical implications

It is no coincidence that most of the successful breeding programmes for nutrient stress tolerance and nutrient efficiency are concerned with micronutrients. The quantities of these elements required by plants are so minuscule, that improved extraction from the soil, without replacement, will not cause future problems.

Breeding for greater efficiency in fertilizer uptake, in order to reduce losses of plant nutrients by leaching or volatilization is also a laudable objective, both for the direct economic benefits that it confers to the farmer, and because it contributes to safeguarding the environment. In this case the objective is to achieve better utilization of fertilizer nutrients and not to mine the soil (Marschner, 1986).

Since the energy crisis of the 1970's, considerable effort is being invested towards breeding varieties capable of producing relatively high yields with low levels of fertilizer applications.

Such programmes have been initiated mainly in developing countries, in view of the high cost of fertilizers, and the inability of the majority of their farmers to purchase yield-increasing inputs.

Fitter and Hay (1987) state that plant species adapted to growing under nutrient stress, are typified by a low relative growth rate, unpalatability (in pasture grasses), and switch of resources from shoot to root development. These are mainly mechanisms for survival at the expense of productivity.

Wild plants adapted to soils of low nutrient availability, such as P-deficient soils, show no deficiency symptoms and have a relatively high P content (Chapin and Bielecki, 1982). This higher tolerance to nutrient deficiency is not related to a higher capacity of the roots to extract soil phosphorus, or to its more efficient use in the plant, but to a slow growth rate, whereby a dilution effect is avoided (Chapin, 1983). This is just the opposite of what is considered as nutrient efficiency in crop plants, namely: rapid growth combined with "a high ratio of tissue dry weight to unit weight of nutrient in the tissue" (Bielecki and Lauchli, 1983).

Borlaug (1976) has reacted to the proposition that it might be possible to breed varieties capable of producing high yields with low levels of fertilizer application by

stating: "we will succeed in producing such varieties of crop plants about six months after utopian political leaders, sociologists and economists produce a new race of man who needs no food in order to grow strong bodies, maintain health, work effectively, enjoy life and speak eloquently". Even if varieties are obtained that can make more effective use of the nutrient reserves in the soil, these will have to be replenished if high yields are to be maintained.

In brief, plants that can produce satisfactory yields without an adequate supply of nutrients, is a pipe dream, similar to the illusion that it may be possible to breed crops giving good yields under killing drought conditions.

Fertilizer use in the developing countries

Fertilizers as a lead practice

Increased use of fertilizers is important even in the early stages of agricultural development, for practical and psychological reasons: practical because returns are quick and little capital is required; the use of fertilizers is probably the single most responsive factor for increased yields per hectare or per unit of water.

Fertilizers also have the great practical advantage that they can be successfully applied by the individual farmer who has the necessary initiative without him being dependent on his neighbours. By contrast, many other practices, such as insect and disease control, are almost certainly doomed to failure, for obvious reasons, unless organized collectively and carried out in a planned fashion over fairly large areas. The *psychological* reasons are that few inputs have such strikingly visible effects on crops. The fertilizer itself is a tangible input, so that the relation between cause and effect is most evident. For these reasons, fertilizer application is considered a 'lead' practice which predisposes the farmer to adopt other improved practices. Every improvement in varieties and management practices that increases yields, also increases fertilizer requirements. Increased amounts are needed to make possible potential yield increases due to improved practices, and to replace additional nutrients removed from the soil.

Fertilizers bear such a highly complementary relationship to other yield-increasing practices, that the amounts of fertilizers used per hectare of land have been found to be a reliable index of progress in the adoption of yield-increasing technologies in general. Williams and Couston (1962) report a 0.87 coefficient of correlation between fertilizer consumption and grain yields in 40 countries. Generally, countries with low levels of fertilizer use are relatively underdeveloped countries; conversely a high level of fertilizer use is the hall mark of countries with a modern, highly productive agriculture and an efficient industrial sector.

The seed-fertilizer revolution

Possibly the most striking and widespread interaction between agricultural production factors is that found to exist between high-yielding varieties (HYVs) and fertilizers. It is the ability to respond markedly to fertilizers which is the main characteristic of the modern varieties and the basic reason for their high productivity.

The term 'green revolution' is generally linked to the introduction of the new so-called 'miracle' high-yielding varieties of wheat and rice. However, it is a fact that, without fertilizers, the impact of the new varieties of these crops is at best small, and frequently imperceptible.

The ineffectiveness of fertilizer use, when applied to traditional varieties with low yield potential, compounded by primitive management practices, is demonstrated by the following example: over all the regions and countries of the fertilizer programme of the Freedom From Hunger Campaign of the FAO, nitrogen had positive effects in 97% of the locations, phosphorus in 90%, and potassium in 85% (Couston, 1967). The most successful fertilizer treatment increased yields by an average of 60% but was profitable in only about 30 of all locations. If the other production inputs had also been introduced, the overall effect on productivity would have been greater. The value/cost ratio averaged from four to eight, indicating that the investment in properly used fertilizers is highly profitable (Olson, 1968).

The three important components of a technology for improved management of Vertisols in the semi-arid tropics, were found to be improved genotype, improved management of both land and crop, and use of fertilizer (Virmani et al., 1989) (Table 11.4).

Improvements in genotype and in management resulted in only small yield increases; applying fertilizer alone doubled the cereal yield, but the effect of the fertilizer was most striking in combination with the other components. The combination

TABLE 11.4

Effects of step-by-step improvements in variety, fertilizer, and management on yields of maize grown during the rainy season on a deep Vertisol

Variety	Land management	Grain yield (kg/ha)	
		traditional (FYM) fertilizer	NPK fertilizer
traditional	traditional	450	1900
	improved	660	2610
improved	traditional	630	2220
	improved	960	3470
LSD $P=0.05$		474	

Source: ICRISAT (1977).

of improved varieties, improved management and fertilizer application, resulted in a fourfold increase in yield.

The authors conclude that “these results highlight the importance of fertilizer application and the synergistic effects that can occur among various inputs when they are used in combination”.

Many more results demonstrate the excellent response of improved varieties to fertilizer applications, provided the moisture régime is adequate; responses are much less certain under variable low-moisture régimes.

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CHAPTER 12

Irrigation: Principles and Practice

Methods of irrigation

In most of the developing countries, farmers still use the primitive and inefficient irrigation methods adopted thousands of years ago. These methods involve considerable labour and drudgery, and are generally wasteful of water (Fig. 12.1). Adopting improved irrigation techniques is an essential first step to the modernization of agriculture.

Irrigation methods are generally designated according to the manner in which water is applied to the soil as follows: surface (or gravity) irrigation, overhead irrigation, sub-irrigation, and low-pressure high-frequency systems.

Occasionally, in order to save a crop from terminal drought, fields are flooded without the land having been prepared for irrigation.

Surface methods

Surface irrigation is still the most important method of applying water to crops and accounts for more than 95% of the land irrigated worldwide; even in the sophisticated irrigation farming of California, where much development of overhead methods has taken place, over 80% of the irrigated area is still surface irrigated (Kay, 1990).

Hillel (1987) defines surface irrigation as “the process of introducing a stream of water at the head of a field and allowing gravity and hydrostatic pressure to spread the flow over the surface throughout the field”.

In surface irrigation, the distribution of water over the land surface is controlled by the land surface itself and not by any mechanical device. The apparent simplicity of the method is misleading. “Good control of the highly variable nature of water movement across a soil surface and its infiltration into the soil over the season is extremely difficult to achieve and would seem to make this one of the most complex methods of applying water ever devised” (Kay, 1990).

The irrigator can modify the manner in which this distribution occurs, (a) by land levelling, to obtain a more uniform surface or to change the slope, and (b) by a



Fig. 12.1. Traditional irrigation still practised in the Middle East. Note short furrows; diversion of the water from the ditch into the furrows by labourer using wide-bladed hoe. Photo Soil Conservation Service, Israel.

combination of length and direction of run of the stream and stream size, appropriate for the soil and topography of the field to be irrigated (Rawitz, 1973a).

All surface systems (excepting emergency flooding) comprise the following components: (a) a distribution system consisting of open ditches or pipelines, with devices for controlling the discharge from the ditches or pipes to the land (often incorporating flow-measuring and pressure-regulating devices); and (b) a land surface arranged so as to direct the flow of water (Rawitz, 1973a).

Flooding

In flood irrigation, the objective is to spread a thin sheet of water over the surface of the land. The water should 'pond' for long enough to refill the storage capacity of the root zone.

If flooding is to be reasonably efficient, a balance must be struck between the size of the stream, the infiltration rate of the soil, the amount of water to be applied, and the size of the units irrigated.

Emergency flooding or wild flooding. Emergency flooding is the last resort to save a

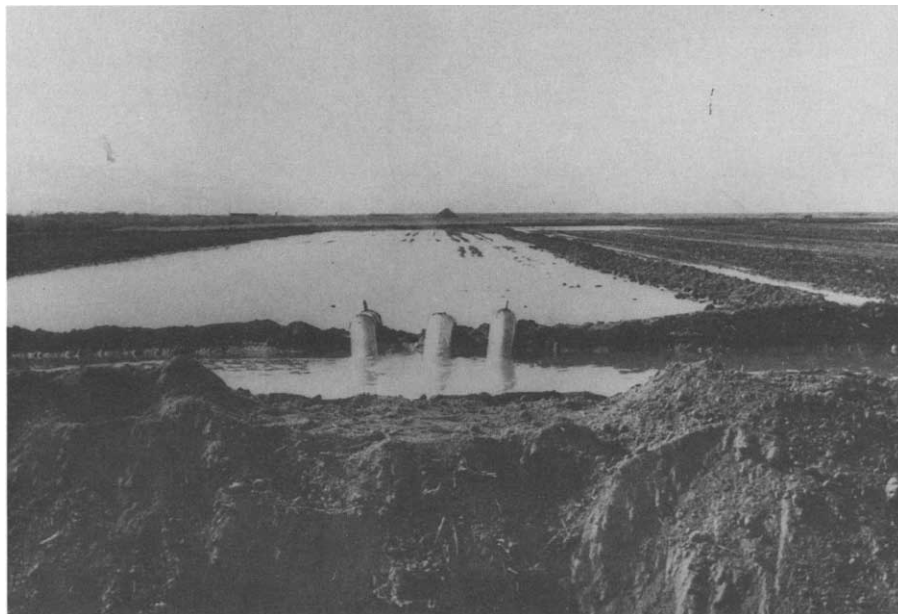


Fig. 12.2. Border irrigation. Photo Soil Conservation Service, Israel.

rainfed crop that is otherwise doomed because of terminal drought. The fields have usually not received any preparation for eventual irrigation.

Wild flooding. In this method, a field that was not initially prepared for irrigation is divided by irrigation ditches into strips from 20 to 25 m wide. The water is diverted into the field from openings in the ditches, and allowed to spread more or less at random. This method is used for irrigating close-growing crops that are suffering as a result of a delay in rainfall, in areas in which irrigation water is available in plenty and at low cost. Wild flooding requires much manual labour, has a low water-application efficiency, and gives very uneven distribution.

Flooding from contour ditches. Irrigation ditches are established on the contour at relatively close spacing, the distance between the ditches depending on the slope of the terrain. Water is allowed to flood down the slope, between one ditch and the next. This is a laborious method – especially if more or less uniform wetting is to be achieved.

Border irrigation (or bordered strip irrigation)

Border irrigation is used on permeable soils on land with a uniform and gentle grade not exceeding 0.5%; steeper slopes are permissible on permanent pasture land. It is the most efficient method for surface irrigation of close-growing crops, such as small grain, lucerne, pasture, etc.

The field is divided into a number of strips between low parallel dikes and so oriented that the water flows slowly in a thin sheet, until it reaches the end of the strip. The border strips should be level between the dikes, and have a slight slope in the direction of the water flow (Fig. 12.2).

In very primitive irrigation agriculture, the strips are very narrow and short – approximately 2×10 m. Only very small streams can be used, and the amount of labour involved is enormous.

In modern irrigation systems, the strips, bordered by dikes 10 to 15 cm high, are much wider and longer. The width of a strip or border is a function of the infiltration capacity of the soil, surface roughness, average slope of the land, and size of the stream (Rawitz, 1973b). To facilitate field operations (cultivation, pesticide control, harvesting, etc.) the width between dikes should be a multiple of the width of the widest agricultural machinery used in the field. The length of the strip (from 50 to 400 m) is determined by the water percolation rate into the soil; the higher the percolation rate, the shorter the border has to be. Cross-slope between borders must be close to nill. The use of laser technology has made the precise grade of the strips possible; thus the irrigation of high intake soils with satisfactory uniformity is feasible (Kemper et al., 1987).

Water distribution is generally not uniform down the slope with a tendency for deep percolation at the head and run-off at the tail (Kay, 1990).

The optimal inflow rate depends on border size, soil infiltration rate, and surface roughness. Commonly used inflow streams vary from 50 to 500 m³/ha (Hillel, 1987). Where expert planning and execution of irrigation are available, the borders can be very large and the irrigator can handle large inflow rates of 500 to 800 m³/ha or even more, without causing erosion, once the crop is well established (Kay, 1990). Until a stand is established, it is possible to irrigate by furrows or corrugations, within the borders.

Small quantities of water cannot be applied to borders; the smallest practical application per irrigation is about 1000 m³/ha, a quantity generally sufficient for 10–20 days (Hillel, 1987).

In brief, the design objective of border irrigation is to ensure maximum possible uniformity of water application by determining the most efficient combination of slope, width of checks, length of run, and size of stream for a given situation, defined by infiltration rate of soil, surface roughness, erodability, and plant cover.

Level basin irrigation

Basin irrigation consists of applying irrigation water to level areas enclosed by dikes. It is the simplest and oldest of all irrigation systems (Burrinhg, 1956), having been practised in ancient Egypt and Mesopotamia, when a river flooded the adjacent plain.

Fairly level fields are well graded and then divided by dikes into rectangular basins, the dimensions of which are adjusted to the kind of soil and the head of stream available. A large stream of water – 150 to 200 m³ per hour – is used to fill these

basins quickly to the required depth. The water then percolates slowly into the soil. The method is suitable both for highly permeable soils and for soils with a very low infiltration rate. As the basin is filled rapidly, uniform distribution is achieved even in permeable soils. As infiltration takes place after the basin is filled, even soils with low permeability will be irrigated evenly. There is no run-off.

The advent of laser technology for levelling land has enabled a high accuracy of levelling; the US Department of Agriculture has set a standard that requires 80% of a basin to be within 15 mm of the mean level. This has led to the use of dead-level basins and enabled basins of over 5 ha to be constructed.

The adoption of dead-level basins in a large irrigation district in Arizona has made possible an increase in application efficiency from 56 to 80%, with a 50% reduction in drainage flows (Van Schilfgaarde, 1979).

Large discharges are required for irrigation (often more than 0.5 m³/s); special inlet structures and control measures are therefore needed to spread water rapidly, whilst avoiding soil erosion problems (Kay, 1990).

If row crops are grown, level furrows can be constructed in the basins. Water can flow in the furrows from either end of the basin, thereby improving advance times and application uniformity.

The large basins facilitate mechanized operations; notwithstanding their size, efficient and uniform application of water is possible (Dedrick et al., 1982). Labour requirements are reduced, and the concentration of water control at a relatively few points make automatic control of hydraulic gates possible (Humpherys, 1986).

Furrow irrigation

Furrow irrigation (Fig. 12.3) consists of running a stream of water in a small channel with a gentle, nearly uniform slope. This method is especially suited to row crops, and can be applied on various soil types and slopes of up to 5%. Water streams that are too small for efficient border-strip irrigation can be used for furrow irrigation. Large water streams in the field ditch are simply divided equally into the appropriate number of furrows; siphon tubes are frequently used for introducing into each furrow a stream of 6 to 10 m³ per hour. In general, long runs are more efficient than short ones, but the optimum length of furrow varies from 50 to 300 m – depending on intake rate, soil texture and erodability, steepness of slopes, and size of the streams.

With furrow irrigation, it is difficult to prevent some erosion, as the soil of the furrow is not protected by vegetation. It is therefore desirable to select a gentle grade – 0.2 to 0.6% – depending particularly on the soil type and size of stream. On steeper slopes, the furrow should be laid out on the contour, within the grades mentioned above.

Efficient furrow irrigation requires skilled management. Large streams are used to achieve rapid advance along the furrows and ensure uniform infiltration along the entire length of the furrows. To reduce run-off, the inflow is gradually reduced to match the changes in infiltration rate.



Fig. 12.3. Furrow irrigation. Photo Soil Conservation Service, Israel.

Because conditions between furrows are never identical, the rate of advance in the furrows is never uniform, and individual streams reach the downstream end of the field at different times. The effect to provide adequate irrigation in all furrows almost inevitably results in overirrigation of some of the furrows. The excess water (tailwater) either accumulates at the lower end of the field, or runs off the field causing erosion or waterlogging (Hillel, 1987). The tailwater can be collected for reuse (cf. p. 159) (Fig. 12.4).

Gated-pipe systems. Aluminium or PVC pipes, up to 30 cm diameter, fitted with control valves and field outlets, provide full control over discharges into furrows, borders, and basins. Pneumatic valves can enable remote control and considerably reduce labour requirements (Humpherys, 1986).

In gated-pipe systems, the maximum outflow uniformity is obtained when the pipeline slopes uphill in the direction of the flow. This is contrary to the normal recommendations for sprinkler and trickle systems (Smith et al., 1986).

Surge irrigation. The introduction of gated-pipe systems was followed by *surge* irrigation for furrows. Surge irrigation has been defined as “the intermittent applica-



Fig. 12.4. Tailwater accumulating in field irrigated by furrows. The tailwater can be collected for reuse. Photo Soil Conservation Service, Israel.

tion of water to the field surface under gravity flow, which results in a series of on-and-off modes of constant or variable time spans” (Bishop et al., 1981).

In order to make possible intermittent flows instead of the traditional continuous flow, two sets of furrows and gated pipes are laid out in a T-configuration. Water is switched automatically from one set of furrows to the other by a valve and automatic time controller (USDA, 1986).

The large surge flows ensure rapid advance along the furrows, and a 50% cut-back can be achieved by running all the gated-pipe outlets at half the surge discharge, once the water reaches the end of the furrows. Surge irrigation simplifies the work of the irrigator (Kay, 1990).

Cablegation. Cablegation is another refinement of furrow irrigation made possible by the gated-pipe approach. It is an automated surface irrigation system in which a single pipeline at the head of the field serves both to transport water and to distribute it to the furrows (Goel et al., 1982).

In this system, a plug, controlled by a cable moves slowly along a pipeline laid on a carefully prepared slight gradient. Outlets in the pipe which feed water to individual furrows are opened by the passage of the plug. As the pressure behind the plug is highest, outlets near the plug have the highest discharge. As the distance from the plug increases, the pressure and flow decrease, creating a cut-back effect.

The speed of the plug is adjusted, so that stream sizes match soil infiltration rates and run-off is reduced. The system has low labour requirements, is simple to operate, and a high degree of uniformity along the furrows is achieved (Goel et al., 1982). Since duration of irrigation can be adjusted without imposing restrictions on farmers' schedules, application amounts can be closely matched to crop needs and soil characteristics (Kemper et al., 1987).

Cablegation is particularly suitable for low-intake soils; the lower the intake rate, the lower the cost of cablegation, because longer and smaller pipelines can be used. When crop canopy is closed, water use efficiency is almost the same as that of trickle systems (Kemper et al., 1987).

Corrugation irrigation In this method, water flows in very shallow (about 10 cm deep) and narrow furrows (corrugations). The water spreads laterally, saturating the area between the corrugations.

This is a system of irrigation that is adapted to close-growing crops, on sloping land and on soils with low permeability. It consists of applying water very slowly in small, shallow furrows, 50 to 150 cm apart, running down the slope from field ditches, or preferably from portable gated pipes made of aluminium or from hosepipes made of various plastic materials – in either case with outlet tubes. These movable pipes make the method considerably more efficient. The outlet tubes are spaced according to the width between the corrugations. The hosepipes can be rolled up and carried from field to field.

The length of time taken by the water to flow from one end of a corrugation to the other varies from 8 to 48 hours; the streams used are very small – 1 to 2 m³ per hour per corrugation. The length of the corrugations varies from 40 to 120 m; the grade is usually 2 to 6%, or occasionally even 10%.

The advantages of the corrugation method are that it makes it possible to irrigate on relatively steep slopes, without causing erosion. No crust forms after irrigation, as water infiltrates sideways, and rises to the soil surface by capillary action. However, this method is very conducive to increasing salinity, because of the large amounts of water used, the capillary rise of the water, and the absence of any leaching effect. It is also generally conducive to excessive watering – especially when irrigation is continued until the entire soil surface is visibly moist.

Advantages and limitations of surface irrigation (Rawitz, 1973a)

The operation of a modern surface system requires more care and understanding than a sprinkler system. In principle, a gravity irrigation system can be designed that is as efficient as other systems, but it is the farmer who must operate it efficiently. If the farmer does not conform to instructions, or the system is not convenient to operate, the best design will not ensure overall efficiency.

The major *advantages* of gravity irrigation are:

- Relatively low initial investment and low depreciation rates, provided the area is reasonably level and otherwise suitable.
- No pressure is required for distribution over the land; surface sources can be diverted directly onto the fields. Energy costs are therefore lower than in overhead systems; this advantage may be partly offset by more water having to be lifted per unit of land (Hillel, 1987).
- Labour costs are relatively low, but operators must be well trained.
- Operation is not influenced by wind conditions.

The major *disadvantages* are:

- Levelling is generally necessary; the removal of top soil impairs soil fertility and lowers yields for many years (cf. p. 684).
- Large but intermittent charges of water are required.
- Flaws in design, and faulty operation of the system make it difficult to control the irrigation stream. This causes increased labour costs, wastes large amounts of water, and results in soil erosion damage.
- Changes in the system that aim to improve efficiency, in the light of experience gained during operation, are difficult or excessively expensive to implement, often requiring a complete redesign of the distribution network.
- Lack of training or experience of the operator may lead to “low application efficiency, waste of water, and the attendant dangers of water-table rise, waterlogging, and salinization” (Hillel, 1987).

Sub-irrigation

Sub-irrigation is achieved by raising or maintaining the water table at a predetermined depth, usually 30 to 75 cm, from which moisture rises by capillary action into the root zone. This is possible when there is a high permanent water table or a relatively impermeable soil stratum not too far from the soil surface.

In one system, the water is held continuously in properly spaced field ditches; the water level in the ditches is regulated so as to maintain a constant supply of water to replace water lost by evapotranspiration. In another system, the ditches are filled periodically and the water is held in them until the surface soil is moist. The excess water is then drained off (Hagan et al., 1967). The drainage system serves alternatively for irrigation and for drainage.

This method is commonly used for organic soils, in order to prevent excessive oxidation and subsidence. It tends to cause salt accumulation in the root layer and can therefore be used only where the soil is regularly leached by rainfall, the irrigation ditches then serving as a drainage system.

Because areas where the water table can be controlled with sufficient precision are relatively limited, sub-irrigation is not widely practised.

Overhead or sprinkler irrigation

Overhead irrigation has been practised on relatively small areas for several decades. The introduction of light-weight aluminium tubing in the 1940's, and more recently of plastic tubing, and the development of quick-coupling systems, has made portable systems technically possible, and thereby economically competitive with the surface irrigation methods.

All sprinkler systems have a number of basic components (Rawitz, 1973b): a source of water under pressure; a system of pipelines to convey the water from the source to the field; and a system of nozzles or orifices through which the water is applied to the land.

Secondary components comprise devices, which can range from simple to very sophisticated, for starting and ending the flow of water; for measuring and for regulating water pressure; for moving the sprinkler line to a new area, etc. The entire system can be monitored and operated by computer.

Conveyance systems (Rawitz, 1973b)

Fixed conveyance systems are those in which all distribution pipelines remain in place; they are usually buried so as to facilitate traffic and avoid damage. Initial cost is high, but labour costs are low. These systems are best adapted for irrigation of perennial crops and are most suitable for automation.

Semi-portable systems also have the main pipelines and submains permanently in place, and generally buried underground. Portable laterals, of aluminium or plastic, carry risers on which the sprinkler heads are mounted. Various devices for moving entire laterals at a time have considerably reduced labour requirements.

Drag line irrigation is a system in which lateral lines are placed at greater intervals and sprinklers are connected by hose-pipes; the need for pipe moves is thereby eliminated, and only sprinklers and hoses have to be moved. The system is operating successfully in many countries (Zadrazil, 1990).

Fully portable systems require a trailer-mounted pump that can be moved to several locations with access to water. Investment costs are lower than in the other systems, but operating costs are higher. They are best adapted for supplementary or emergency irrigation once or twice a year.

Discharge systems (Rawitz, 1973b)

Static sprinklers. Static sprinklers are mainly used in private gardens, vegetable plots and for preventing frost damage in orchards.

Static-nozzle lines consist of aluminium pipes, 5–10 cm in diameter, with several rows of holes drilled into them radially, to distribute the water at different angles. They operate at relatively low pressure, the width of wetting being determined by the pressure. Their use is limited to highly permeable soils.

Oscillating-nozzle lines consist of a metal pipe, of 25–37 mm diameter, resting on

supports. Brass nozzles are tapped into the pipe, which is oscillated by a hydraulic motor driven by the irrigation flow. Once very popular for vegetable crops they are still found only occasionally in plant nurseries.

Rotating sprinklers: rapidly rotating sprinklers have two to four radial arms with nozzles at their ends, and operate at relatively low pressure. Their main use is in private gardens. Slowly rotating sprinklers are the main type in use in agriculture. One to two nozzle sprinklers are the most common. They make a complete revolution in 30–120 s, driven by the jet of water from one nozzle impinging on a spring-loaded impact arm, or a counterweighted arm without a spring. They are reliable and easy to maintain and repair.

Giant sprinkler machines. Rising labour and energy costs have led to the development of many different self-contained, integrated and self-propelled so-called giant sprinkler systems.

(1) *Centre-pivot system.* The largest single sprinkler system in use in the US is the centre-pivot system that has “unique capabilities that recommend its use for field crops in desert land development” (Richardson and Koelzer, 1979). It has introduced a level of automation into irrigation which was previously not thought possible and enabled areas of up to 100 ha to be irrigated by a single machine (Kay, 1986).

A centre-pivot sprinkler consists of a series of sprinklers mounted on a lateral pipe, 50–800 m long, mounted or carried by a row of five or more mobile towers. One end of the lateral is fixed on a pivot pad. In a rotating system, the unit rotates around a center pivot where water is pumped into the pipe. The movement of the towers around the pivot is controlled by the outermost tower and an alignment device, using microswitches, to move the other towers in conjunction with the outer tower.

Once the system is set for a given application, it advances continuously in a circle, without need for human intervention, other than monitoring (Phene et al., 1985).

The rate of advance may vary – a complete circle may require from 18–24 hours to 3–4 days, and water rates are directly proportional to the rate of travel (Richardson and Koelzer, 1979).

The limitations of the centre-pivot system are: (a) loss of 10–20% irrigated land area in the corners of square fields; (b) inefficient lateral hydraulics; (c) excessive water application rates at the outer end of the lateral (Kay, 1990); and (d) high energy requirements, ponding and run-off on fine-textured soils of low permeability caused by the high discharge rate at the outer end of the system (Smith et al., 1982).

(2) *Lateral-move systems (Fig. 12.5).* The limitations of the centre-pivot system led to the development of lateral-move systems which move up and down a field, irrigating square or rectangular plots, and thereby providing better coverage of the entire field. These systems can traverse 1 ha for 1 kWh of energy, equivalent to 0.16 L of diesel fuel and therefore use one-tenth of the energy of conventional sprinkler systems (Lyle and Bordovsky, 1980). They can also serve for the application of



Fig. 12.5. 'Valley' lateral-move giant sprinkler system, pre-irrigating an area prior to sowing. Photo Holland Dreves Reilly, Inc.

herbicides, fertilizers, pesticides, and even seeds by fluid drilling (Voorhees et al., 1978). Not more than 5% land area of a rectangular field is lost for wheel track and the main tower (Phene et al., 1985). They are, however, more costly to install and operate than the centre-pivot system (Howell and Phene, 1983).

Rainguns. Large *mobile rainguns*, that can irrigate up to 4 ha in one machine setting are also used where labour-saving systems are required. However, their high pressure of operation requires high energy inputs (Kay, 1990).

Advantages of overhead irrigation. Overhead irrigation has made possible, both technically and economically, the irrigation of terrain that is too steep or too uneven for surface irrigation, as well as of very sandy soils, and therefore makes available for development large tracts that were formerly excluded.

On land with a more regular topography, levelling is not as essential as for surface irrigation, and certainly does not need to be as elaborate. Not only is the expense involved in levelling often avoided when sprinklers are used, but also great damage

to the land, due to the removal and/or covering of the top soil, which sometimes requires many years of expensive reclamation with resulting yield losses.

Water application can be far more uniform with sprinkler systems than with surface irrigation, except during times of high winds. The amount of water required can be calculated and then applied with great precision, so that overall water use is more efficient with sprinkler irrigation than with surface irrigation, and soil erosion damage can be reduced.

The elimination of field ditches increases by approximately 5% the net area available for crop production, facilitates the movement of farm machinery, decreases conveyance losses, and eliminates the cost of ditch maintenance.

The manual work involved in sprinkler irrigation is less arduous and requires less skill than that needed for gravity irrigation. It is also easier to train the operators. Mistakes or negligence on the part of the operators have less disastrous consequences than in the gravity systems.

In regions in which light frosts occur occasionally, sprinkler irrigation can be an effective means of preventing frost damage.

Disadvantages of overhead irrigation. The capital investment is relatively high, and for many countries it may be difficult to maintain specialized equipment and obtain spare parts (Kay, 1990).

Most sprinkler systems require a minimum pressure of 2 atm to operate satisfactorily; this pressure must generally be provided by a pump which increases energy requirements and water cost.

Evaporation losses from sprinkler irrigation can be significant; their magnitude depends on the temperature and relative humidity of the area, saturation deficit, wind velocity, size of nozzle, and the working pressure. The greatest losses result from wind velocity and system design and installation (Worthington, 1977). Wind speeds above 12 km/h make the irrigation inefficient; for this reason, overhead irrigation is usually confined to certain hours of day or night. Giant sprinklers have been developed that compensate for wind effects by variable rotation speeds.

The spread of plant pathogens is facilitated and a number of bacterial and fungal diseases is more severe under sprinkler irrigation than under gravity or drip irrigation.

Some crops, such as citrus, are sensitive to the salt from irrigation water absorbed through the leaves. With overhead irrigation, salts are toxic at concentrations that would be safe with other irrigation methods (Rawlins, 1981).

Another drawback of overhead irrigation is the need for scheduling irrigation so as not to wash off plant protection chemicals before they have taken effect.

All in all the drawbacks of overhead irrigation are more than offset by the advantages, and the areas under this method have increased markedly, both absolutely and in relation to surface irrigation.

*Low-pressure high-frequency systems**Drip or trickle irrigation*

Development. Drip irrigation makes it possible to apply slowly, precise amounts of water to precise locations; it is therefore a distinct advance in irrigation technology (Gregory, 1990).

Drip irrigation is a relatively recent method and is being increasingly adopted worldwide in dry regions. Because of certain features that are unique to this system it will be discussed in more detail than the long-established methods described above.

Drip irrigation was borne of necessity. When the first agricultural settlements were established in the early 1950's in the Arava, a desert in the southern part of the Israeli section of the Great Rift Valley, the preconditions for agricultural production were grim indeed. A harsh, extremely hot and dry climate, sandy and gravelly undeveloped and unfertile soils, very limited water resources with high salinity, and an average annual rainfall of only 50 mm, appeared to present insuperable obstacles to economically sustainable agricultural production.

The physical structure of the soil and the limited amounts of water available, precluded the use of any surface methods of irrigation. Overhead irrigation proved to be inefficient and to cause more problems than it solved. Irrigation efficiency was extremely low: losses due to evaporation in the dry desert atmosphere were considerable and drift caused by the strong hot winds added to the losses. The high-salinity water scorched the leaves, and the combination of moist leaves and high temperature was conducive to the spread and intensity of foliar diseases.

The idea of reducing losses from evaporation by placing underground small-diameter pipes with regularly spaced orifices for water discharge had been tested by an irrigation engineer, S. Blass (1964), some years previously. The idea was sound, but its implementation in the field was obstructed by the rapid clogging of the orifices by roots that penetrated the pipes.

The early settlers in the Arava, unhampered by preconceived ideas, decided to lay the Blass pipes on the surface, and thereby avoid clogging of the orifices by roots. This time, the idea was not only sound, but also practical. Experience soon showed that the fear that losses by evaporation would be considerable if the pipes were above ground, were not justified. Naturally, problems were encountered, but with investments in research and development, the technology that is now known as drip irrigation gradually evolved. The Arava is now a major supplier of out-of-season high-value crops to the mainly European markets. In field trials in the Arava, winter tomatoes produced 58.3 t/ha with drip irrigation, compared to 35.8 t/ha with sprinkler irrigation, an increase of 63%. A similar yield increase (70%) was obtained with winter muskmelons. Salt-sensitive cucumbers, that formerly could not be grown in the Arava, produced significant yields (Shoji, 1977).

Principles. Drip irrigation is based on the discharge of small amounts of water,

under relatively low pressure, to a relatively closely spaced grid of perforations or emitters in plastic distribution pipes, placed on the surface of the soil (Heller and Bressler, 1973). Water emission can be in the form of small drops, continuous drops, tiny streams, or miniature sprays (Bucks et al., 1982).

Generally, only part of the soil is wetted, and the actual rooting volume is usually less than 50% of that of a conventionally irrigated soil. The wet portion of the soil is kept continuously moist without being saturated (Hillel, 1987).

Components of the system. A drip irrigation system comprises the following components: *a main control station* – comprising a pump, a backflow prevention device, a primary water filter, a water meter, pressure regulators, and couplings for a fertilizer tank.

To this ‘control station’, a rigid plastic tube is connected, the diameter depending on the required length and discharge. To this main tube are attached distribution laterals of 10 to 25 mm flexible plastic tubing of up to 50 m in length, placed on the ground, along the row crop to be irrigated. In the lateral tubes are calibrated emitters from which water trickles at the rate of 1 to 8 litres/hour. Spacing between emitters is a function of the crop, soil type, and rate of discharge of the orifice. These distances generally vary from 50 cm on sandy and sandy-loam soils, to 150 cm on heavy soils (Goldberg and Shmueli, 1970).

Different types of emitters have been developed, with the objective of reducing clogging by combining the low discharge with as large an opening as possible (Heller and Bressler, 1973). The smaller the orifice, the greater the danger of blockage; conversely, increasing orifice size requires a relatively low operating pressure, resulting in non-uniform discharge when there are elevation changes in the topography (Rawitz, 1974).

Flow regulators are frequently attached to each lateral. The pressure within the laterals is generally 1 to 3 atm.

The system can be automated by simple automation equipment consisting of electrical, mechanical, or battery-operated time clocks that activate pumps and solenoid valves at selected times of the day. More sophisticated systems have also been developed that include soil moisture sensing devices, computer interfacing, and remote controllers (Bucks et al., 1982).

These authors foresee that future drip irrigation systems will probably use micro-processors that monitor not only soil moisture, but also hydraulic pressure, flow rate, chemical injection rate, and weather data.

Soil moisture régime. Drip irrigation is not only a technical innovation, but also embodies an entirely new approach to the supply of water to crops.

In drip irrigation, water is applied slowly and frequently, at a predetermined rate. Moisture content of the wet zone remains constant within a narrow, predetermined range of soil moisture tension, without causing waterlogging and soil aeration prob-

lems. Optimal conditions of water supply are therefore maintained throughout the growth of the crop. Monitoring devices placed in the field ensure that soil moisture is held as near field capacity as possible (Shoji, 1977).

Operation. Under arid conditions, most crops are irrigated daily, usually at the rate of 0.8 of the evaporation from a class-A pan (cf. p. 628). The emitters should not be placed too near the stems of individual plants to avoid stem diseases; the optimum distance is 5–30 cm. A greater distance has an adverse effect on plant development and yield. The wetted area may extend as much as 50 cm from the emitters in coarse-textured soils, and it is in this wetted zone that the roots are concentrated (Goldberg and Shmueli, 1970). Bucks et al. (1982) suggest that, in arid regions, at least one-third of the potential root zone should be wetted, and up to two-thirds might be preferable for better margins of safety in case of interruptions in water supply.

The rate of horizontal and vertical movement of water is a function of soil type and emitter discharge rate. The soil is wettest under the plants and water potential decreases laterally.

Fertilizers can be applied continuously or intermittently through the irrigation system (see fertigation, cf. p. 557) by passing one-third to one-quarter of the water through the fertilizer tank. Another possibility is to combine irrigation with soil disinfection at the beginning of the growing season.

The emitters must be regularly checked; clogging adversely affects the rate and uniformity of water application, increases maintenance costs, and results in crop damage and reduced yield, if not detected early (Bucks et al., 1982).

Clogging of the orifices can best be reduced by preventive maintenance (Bucks et al., 1982): removing larger particles from the water by using settling basins and smaller particles by screen or sand filters; chemical water treatment (chlorinating the water for 20 minutes per day at the rate of 10 mg/kg will eliminate slime (Shoji, 1977)); orienting the orifices upwards and periodical flushing of trickle lines; field inspection.

To reduce clogging, methods for automatic or manual flushing have been developed and emitters are manufactured that are less likely to clog (Marsh, 1977).

Where high-salinity water is used, extensive leaching may be necessary before the next crop is planted; sometimes flood or overhead irrigation is indicated for this purpose (Bucks et al., 1982).

Frequency of irrigation varies from a daily to a weekly schedule, depending on the type of crop, soil, season, climatic conditions, and water quality. Longer intervals between irrigations give the deeper water penetration required by deep-rooted crops and move salts further away from the plant; frequent irrigations are desirable for shallow-rooted crops, as they reduce deep percolation on coarse soils and enable the use of brackish water (Bucks et al., 1982).

Advantages. Bucks et al. (1982) state that the greatest potential for drip irrigation

is in situations where water is expensive or scarce, for marginal soils, and for high-value crops.

Optimal soil moisture. The moisture regime and soil aeration are optimal under the tricklers for the reasons explained above.

Economy of water. Due to:

- (a) The possibility of supplying the exact quantity of water needed, with a minimum of losses. At the slow rates of application practised, water percolates immediately downwards and sideways into the soil, reducing evaporation losses to a minimum. Nor is there any significant run-off or percolation. With good management, growers in Hawaii have reported increases in efficiency of 40–60% through trickle irrigation (Shoji, 1977).
- (b) Restricted water supply: only a limited volume of soil is wetted, making possible a considerable saving of water. No loss in yield is thereby involved. The restriction in volume of the root zone is compensated for by the optimal conditions of water and nutrient supply where the major portion of the active root system is concentrated.
- (c) High uniformity of application.
- (d) Losses due to evaporation are reduced because of the limited soil surface wetted; losses due to run-off are avoided on steep hills and on low-permeable or crusted soils.

Actual savings in water will depend on the crop, soil, environmental conditions, and management efficiency (Bucks et al., 1982).

Minimizing salinity hazard. Because of the high water potential maintained in the root zone throughout the growing period, adverse effects on the crop from salinity are generally insignificant; therefore water with higher salinity levels can be used in drip irrigation than in other irrigation methods. The salts are displaced beyond the main root zone by an advancing front of water from the orifices of the drip system. Burning of foliage due to accumulation of salts on the leaf surface is avoided.

Yields of sweet maize, grown with drip irrigation using water with a salinity level of 3000 micromho/cm, gave yields equal to those obtained with sprinkler irrigation using non-saline water (Goldberg and Shmueli, 1970).

Bernstein and François (1973) found that brackish water reduced yields far less with drip irrigation than with furrow or sprinkler irrigation, as shown in Table 12.1.

Disease prevention. The dry foliage reduces risks of infection by foliar diseases; transmission of pathogens by water movement or splashing is also avoided.

Nutritional balance. Can be optimized by daily supply of the exact amount of fertilizers needed; leaching of nitrate is avoided (Kafkafi et al., 1977) (cf. p. 428).

Energy savings. At the edge of the field, the pressure of a typical drip-irrigation system is about one-eighth of that required for a sprinkler system. However, the main source of energy saving is the reduction in the amount of water pumped, because of higher on-farm efficiency (Shoji, 1977).

TABLE 12.1

Effect of brackish water on yields with different irrigation systems

Water quality (EC=dS/m)	Yield reductions compared to low-salinity water ^a		
	drip	furrow	sprinkler
3.8	15%	54%	94%

^aEC=0.7 dS/m, dS/m=1 mmho/cm.

Ease of management. The system can be operated 24 hours a day, even when winds are blowing. A minimum of manpower is required and the system can even be completely automated.

At a small distance from the drip line, the soil surface is completely dry, permitting tractor, equipment and personnel traffic during various field operations. The uniform growth, resulting from uniform water application, facilitates mechanical harvesting. The dry areas remain weed-free, and weed control on the wetted areas is facilitated.

Fertilizers, herbicides, insecticides, fungicides can be applied through the irrigation system.

There are no problems of scale, as the system can be used on small plots as well as on large farms.

Irrigation of problem soils. Lands that were formerly considered unsuitable for irrigation, such as those with minimal water storage capacity (e.g., coarse sands and gravels) can now be irrigated (Hillel, 1987). As there is no run-off, the system can be used on hilly terrain. With drip irrigation, avocado orchards in San Diego are planted on slopes of 50–60%, without problems of soil erosion (Shoji, 1977).

Limitations and problems. The following limitations and problems arise:

Cost. Initial investment and annual maintenance costs are relatively high, and are generally in the same range as solid-set sprinklers (Marsh and Gustafson, 1971).

The method is not suitable for closely planted crops, such as wheat or lucerne, because the amount of tubing required would make the system too costly, even in rich countries.

Operational. The most serious problem in drip irrigation is clogging of the emitters unless preventive measures are taken (Bucks et al., 1982).

Even with careful filtration, some clogging by fine silt, clay particles, and organic slime can occur. Some waters have to be treated with chlorine or other chemicals to control organic slimes.

The advantages of a limited volume of wetted soil are offset by the vulnerability of the crop to relatively short interruptions in water supply. Hence the need for continuously maintaining the system in perfect working condition, which in turn requires skilled operators and easy access to spare parts; these requirements may impose severe constraints in adopting the system in developing countries (Hillel, 1987).

Salinity. Under drip irrigation, a salinity profile develops which consists of three main zones: an upper zone, in which salinity decreases as the distance from the nozzle increases; a wide intermediate zone, where salinity values are low; and a lower zone where the salinity increases with depth and with distance from the nozzle (Goldberg and Shmueli, 1970). In arid areas there is therefore a localized concentration of salts, which must be leached out in the off-season, using one of the conventional irrigation methods, preferably by sprinklers.

In semi-arid regions, with sufficient rainfall and natural drainage, no salinity problems are anticipated.

Subsurface drip systems. Apparently, the wheel has turned a full circle! Bucks et al. (1981) and Phene et al. (1982) report using subsurface drip systems successfully to produce several crops consecutively without major changes in cultural practices or replacement of the tubing. Earlier problems with clogging have been reduced, and the system is widely used in the western USA on small fruit and vegetable crops and in Hawaii on sugar cane (Bucks et al., 1982).

The advantages of the subsurface system include saving of labour, little interference with cultivation, and longer life of the tubing.

Other low-pressure high-frequency systems

Bubble irrigation. Bubble irrigation, as described by Richardson and Koelzer (1979), is similar in principle to drip irrigation, but requires much lower pressure. The existing elevation of ditches or pipes used for surface irrigation is generally sufficient to provide the necessary pressure (Rawlins, 1977). The system does not require filtered water. Discharge rates are higher and range from 1 to 4 L/m.

A bubble system consists of a network of inexpensive, low-pressure plastic pipes of 5–10 cm diameter in which water flows by gravity. Small hoses (6–12 mm) anchored to stakes, replace the emitters of the trickle system. The flow rate to the plants is controlled by lifting the small hoses to the required height. Because the emitter discharge generally exceeds the infiltration rate of the soil, a small basin is usually formed below the emitter.

The method has the same overall advantages as drip irrigation but is less expensive and does not have the high energy requirements of the latter. It cannot, however, be operated on land with non-uniform soil.

Micro-sprayers. Micro-sprayers (also known as mini-sprinklers or spitters), like the drip system, apply water only to a fraction of the ground surface. They eject fine jets

that fan out from a series of nozzles, mounted on risers, each of which covers about one square meter. The volume of soil wetted is larger than in drip irrigation (an advantage on soils with low water-holding capacity), the risks of clogging of orifices is smaller, the requirements for filtration less stringent, and installation costs somewhat lower. Micro-sprayer systems use the same tubing network as the drip system and pressure requirements are similar (Hillel, 1987).

Porous wall or sweating lines. The irrigation lines are made of porous spunbonded polyolefin material, with pore sizes of 4 microns and 50% porosity. The lines are placed adjacent to the rows; burying at a depth of 5–10 cm in the soil is recommended in order to avoid light-degradation of the plastic. A soil chisel mounted on a toolbar can be used to lay the tubing underground (Joyce, 1976).

Hybrid systems

In order to achieve significant savings in energy and water over the systems described above, low-pressure systems have been developed (Kay, 1990) that extend the bubbler or drip irrigation concept (cf. p. 598, 603) to large-scale row crops, thereby combining the advantages of both approaches (Phene et al., 1985). These systems use lateral-move sprinkler system mainframes that have drop structures or tubes to deliver water as a continuously moving stream to each row (Bucks et al., 1982).

The *low-energy precision application* (LEPA) is such a low-pressure system: instead of spraying the water into the air, it uses drop tubes to place the water directly into tied furrows. Trials have shown that the system achieves a water application efficiency of 99%; the pressure required was only 7–27 kPa (Lyle and Bordovsky, 1980).

The *travelling trickle irrigation system* (TTIS) is a similar system, with drip irrigation lines trailing behind it; levels of water application efficiency and of energy use reported are similar to those of LEPA. The system is partially powered by photovoltaic cells. Five field towers follow the main tower laterally across the field, on one side of the irrigation ditch, by using a laser guidance control. The pumping rate and travel speed are dynamically adjusted for precise water application based on data from a nearby weather station; a microcomputer is used to control the system. Because of the high instantaneous application rate, the water applied exceeds the infiltration rate. In order to avoid run-off, it is necessary to use a system that retains the water. Various techniques have been adopted for this purpose, such as the tied furrows used in LEPA, and vertical mulching (Phene et al., 1985).

The advantages of TTIS are: low-pressure operation; the drop tubes eliminate wind drift and reduce evaporative losses, and do not wet the foliage, allowing irrigation with marginal quality water; the application rate can be controlled through speed control, providing flexibility of irrigation scheduling; the automatic laser alignment and speed control systems ensure uniform application of water; automatic remote operation by computer terminal; energy conservation (Phene et al., 1985).

The disadvantages are: complexity of the mechanical and electrical components,

requiring a high level of managerial competence; high capital investment; the need for precise cultural operations (Phene et al., 1985).

Choice of method of irrigation

Each irrigation method has its potential advantages, limitations and drawbacks. The following factors determine the choice of irrigation method: topography; soil characteristics; environmental factors, the crop(s); the quantity, quality, and cost of available water; energy considerations.

Sprinkler irrigation can be used for all crops (even upland rice); furrows are suitable for row crops; basins are the only method suited to paddy rice, but can also serve for other cereals and for forage crops; border strips are used mainly for fodder crops, pastures, and close-rowed cereals.

The steepness of the slope, its direction and regularity, are the principal topographical factors to be considered. Surface irrigation methods require land of fairly uniform and not excessive slope. Levelling is usually necessary to achieve this requirement; slopes should not exceed 4%, or else excessive levelling operations will be required. Land with a very irregular topography should be irrigated by sprinklers, corrugations, contour furrows, or flooding from contour channels. Level land or land with a regular and gentle slope can be irrigated by furrows or flooding between borders.

The infiltration rate of the soil is of great importance in deciding on the irrigation method to be used. Generally, the rate of intake decreases rapidly from soon after irrigation is started, until it reaches a fairly constant level. Surface-flow methods are not very suitable for soils with a very high intake rate, while in ponding methods, very rapid filling of the basins is essential if uniform distribution is to be achieved. Soils with a very low infiltration rate require irrigation methods in which the water can be ponded on the soil surface for a relatively long period.

Soil texture and structure also affect the choice of irrigation method. On very light soils, only sprinkler and drip irrigation are efficient. Soils with a very unstable structure may break down easily under irrigation, to form hard, impenetrable crusts. Such soils require very careful irrigation – especially during the period of germination and emergence. Under these circumstances, drip irrigation is the best choice.

The size of the head of water available must also be considered. Small heads can be used for furrow irrigation or small borders. Large heads require appropriate irrigation methods if the water is to be controlled properly, and if damage to soil, crops, and the waterworks, is to be avoided.

When water with a high content of salts is used, irrigation methods must be designed so as to make it possible to leach the salts periodically from the soil. Certain irrigation methods, such as corrugation or sub-irrigation, have to be avoided under these circumstances.

The nature of the crop must also be considered. High-value and perennial crops

can justify elaborate irrigation systems that would not be justified for low-value or annual crops. Furrow irrigation is suitable only for row crops.

When quantities of water are restricted or water is expensive, the efficiency of irrigation assumes a still greater importance than under less stringent conditions, though maximum efficiency of water use should always be the aim.

Irrigation efficiency is greatly increased as one moves successively from flood irrigation to furrow, sprinkler, or drip irrigation. But each increase in efficiency involves moving to a higher technology, a higher capital investment, higher energy consumption, and more complex planning. Edmunds (1979) concludes that the choice of irrigation method depends on a trade-off between water economy on one hand, with energy and capital costs for any specific crop on the other hand.

The choice of an inappropriate method of irrigation results in the squandering of large sums of money that have been invested in soil preparation and purchase of equipment; moreover, operating costs may be unnecessarily high, with inefficient use of labour and water. Yields may be reduced by an excess of water in one part of the field and a shortage in another.

Irrigation management

Irrigation efficiency

Efficiency in water use – a crucial issue

In Ch. 4, the current situation of world water resources was reviewed; all statistics indicate that water is a scarce resource worldwide, and that it must be carefully husbanded. Aquifer depletion, international and internal conflicts for water rights, the need to conserve energy, and the overriding need to maintain soil fertility, contribute to the urgency of improving irrigation efficiency.

Nowhere are the problems more acute than in the dry regions where water is generally the key to agricultural development, and also a major factor in overall development. It is in these regions, in particular, that the inefficient use of water for irrigation has severely limited further development of irrigated agriculture (Kay, 1990).

In those countries which are fortunate in having abundant water resources, inefficient and wasteful use of water unfailingly leads to disastrous consequences (see Ch. 13).

Agriculture is the major consumer of water in drought-prone regions, and considerable savings in water can be achieved by improving the efficiency in water use by crops, and by improving the maintenance and efficiency of existing irrigation networks. Hence, there are two basic approaches for expressing water use efficiency in irrigation agriculture: (a) an agronomic-plant physiology approach, centred on yield as related to water input (water use efficiency), and (b) an engineering-planning

approach concerned primarily with the technical performance of the irrigation network (irrigation efficiency) (Shmueli, 1973).

Water use efficiency relates to all water received by the crop, whether from precipitation or irrigation; it is therefore equally relevant to both rain-fed and irrigated farming. For this reason this topic has been treated in detail in the chapter on plant-soil-water relationships. Irrigation efficiency, as its name implies, is concerned exclusively with irrigation agriculture and is therefore treated separately in this chapter, though in agricultural practice all aspects of water use efficiency must be considered in their entirety.

Irrigation efficiency defined

Irrigation efficiency (E_i) is usually defined as the ratio between the quantity of irrigation water that is stored in the soil and is available for consumptive use by crops, and the total quantity of water supplied from source (Hagan et al., 1967),

$$E_i = 100 \frac{W_{et}}{W_a},$$

where W_{et} = volume of water in a specified area transpired by plants and evaporated from the soil, and W_a = volume of water applied to a given area. E_i represents the *overall irrigation efficiency* of an irrigation project, between diversion or source of flow, and the root zone in the farmer's field (Worthington, 1977).

In order to assess properly the contribution to E_i of individual components of the irrigation network, three components are considered:

- (a) *conveyance efficiency*, which is the ratio between the quantities of water from the source and that which reaches the irrigation area;
- (b) *distribution efficiency*, which is the ratio between the quantities of water that reach the fields and that supplied from source;
- (c) *farm efficiency*, which is the quantity of water under the farmer's control and that is effectively stored in the root zone.

Bos and Nugteren (1978), from world survey data of large irrigation areas, found conveyance efficiencies of 80%, distribution efficiencies of 70%, and farm efficiencies of 60%, for flood methods of irrigation. This amounts to an overall project efficiency of about 34%.

Distribution efficiency

Conveyance losses are practically nil when water is conveyed to the field through pressure pipes that are in perfect condition. However, leaks in the system, faulty valves, or other results of neglect, frequently cause considerable losses of water.

The conveyance losses in open ditches are usually considerable, and are due to seepage from the ditch, transpiration by aquatic plants or those growing on the ditch banks, and, to a far lesser degree, to evaporation. The losses in an average unlined

canal have been estimated as one-third of the water conveyed (Arthur and Thoroky, 1967).

In Algeria, about 40% of the water is lost during conveyance from canals in sandy soils. The Kara-Kum canal in the former USSR lost by seepage 43% of the overall discharge at its head, in the first year of operation (Worthington, 1977).

Factors affecting losses from conveyance systems include climatic and soil conditions, density and length of the canals. In unlined canals, losses are related to the hydraulic conductivity of the soil, the depth of the groundwater table in the area near the canals, and discharge and velocity of water (Worthington, 1977).

A variety of *linings* can be used to reduce these losses (Fig. 12.6), including hard-surface linings (of asphalt, concrete, films of plastic), buried-membrane linings (hot-applied asphalt, plastic film), and earth linings (betonite-soil mixtures, compacted earth-blanket linings of impervious soil). One of the less costly linings, favoured for sandy soils, is colmation, which consists of sealing the pores of the soil with colloidal soil particles which enter the pores during infiltration. Introducing sodium salts into the soil lining the canals, causes the soil to swell and become impervious (Worthington, 1977).

In order to reduce evaporation losses from the canals to a minimum, the water surface should be reduced by building the canals as deep and narrow as is feasible.

A major disadvantage of the canal system is its lack of flexibility. The system generally provides water to several farms on a fixed time schedule, irrespective of rainfall or high evaporative demand, and is therefore unable to respond rapidly to changing water requirements (Kay, 1990). According to Merriam (1977), this lack of flexibility is the biggest single cause of low efficiency.

Flexibility in supplying farm water requirements has been improved through several approaches: canal night storage (in the Gezira Project); automation of canal control gates; downstream control systems; pipe systems which respond more rapidly to changes in demand than open canals (Kay, 1990).

Closed or semi-closed pipe systems can be an alternative or a supplement to a canal system. They are usually more expensive than open ditches, but the resultant improved water control leads to improved crop yields and considerable water savings (Merriam, 1985).

When farmers' confidence in supply is improved, they are ready to stop the flow of unneeded water instead of 'hoarding' it in the soil (Merriam, 1985), a common practice which is conducive to waste of water, waterlogging, and high water tables.

Irrigation efficiency on the farm

After irrigation water reaches the farm gate, control by the public body, cooperative or private supplier of the water ends, and the farmer takes over.

Conveyance losses. The causes of losses in the distribution system on the farm are similar to those of the conveyance systems that bring the water to the farm. A closed



Fig. 12.6. Irrigation ditches lined with concrete, using portable slip forms, conserve irrigation water and reduce erosion in gravity-irrigation systems. By courtesy of the University of Wyoming.

pipe system, if properly maintained, will eliminate most of these losses. However, in developing countries, the majority of the farmers cannot afford such a system, and the use of open, unlined ditches, with resultant considerable water losses, is general.

Water application efficiency. Water application efficiency on the farm depends on many factors: soil topography, texture and structure; the vegetative cover; the degree of care exercised in levelling and preparing the area to be levelled, the experience and ability of the irrigator: the frequency of irrigation, the method of irrigation, the depth of the root system, and the efficiency with which the crop uses available water.

If excess water reaches the end of the field, run-off can become a problem; this can be reduced by adjusting stream flow to match infiltration along the strip or the furrow. The run-off can also be recycled (cf. p. 159) (Hillel, 1987).

Gated pipes provide one of the simplest and most effective ways to improve on-farm flexibility and efficiency of canal water supplies.

Soil factors. Losses of water in the soil profile consist of water that becomes unavailable to plants and of percolation beyond the root zone. The amount of physiologically unavailable water is greatest in heavy soils, and negligible in sandy soils with a

low exchange capacity. Excessive application rates lead to run-off and also cause losses by percolation into the subsoil.

The run-off from the field is not only a waste of water, but also causes erosion and washes away fertilizers and pesticides which may pollute water sources downstream.

Water percolation beyond the root zone is not always to be considered a loss; as will be indicated in the next chapter, it is frequently essential and caused deliberately, in order to leach salts beyond the root zone. It is the unplanned, unnecessary excess amounts of water that are undesirable and even dangerous, as they usually cause waterlogging and eventually a rise in the water table.

Evaporation losses from the surface of the land will be relatively minor when intervals between irrigations are long and increase in importance with an increase in the frequency of irrigation.

Cultivation methods, such as proper tillage, weed control, and mulching, may reduce evaporative losses from the soil surface. The magnitude of the losses depends also on the irrigation method used: in overhead irrigation, evaporation losses from the air may be of considerable magnitude, depending on temperature, relative humidity, saturation deficit, wind velocity, size of nozzles, and working pressure (Worthington, 1977). Losses may be reduced by irrigating at night, and when wind velocities are low.

Tied furrows, a system of cultivation widely used in the tropics to conserve rain-water (cf. p. 708) can eliminate run-off under high-pressure as well as low-energy sprinkler systems (Lyle and Bordovsky, 1980).

Irrigation methods. Kay (1986) summarized the potential efficiency of different surface irrigation methods, and the factors conducive to its decrease. He indicated that potential efficiency for basin irrigation is 90%, for borders 80%, and for furrows 90%.

In all three systems, poor land preparation reduced efficiency by 10–20% unflexible irrigation schedules by 10–20%, and different soil types within basin, border or furrow, respectively, by 10–20%.

Irrigation scheduling

Objectives

The basic objective of irrigation scheduling is to maintain or improve crop yields by avoiding both excessive application of water and excessive soil moisture depletion. Proper scheduling saves water and provides an opportunity to control plant growth and development in a way that optimizes productivity (Grimes and Dickens, 1977). A scheduling programme should forecast dates when soil moisture content reaches a critical level, as well as the amount of water required.

There are two alternative objectives for scheduling irrigations: to achieve either maximum yield per land area, or maximum yield per unit water. Most farmers would probably prefer the first alternative, but where water is scarce or expensive, it is the second alternative that asserts itself (Bucks et al., 1982).

Irrigation scheduling is used successfully in many parts of the world and has been shown capable of saving 15–25% of the water used for irrigation (Gilley and Watts, 1977).

With the advent of irrigation methods that are capable of applying light irrigations of high uniformity, such as drip irrigation and high-frequency overhead systems, it is possible and practical to maintain soil water potential effectively between relatively narrow limits, and avoid plant stress completely. The high water potentials maintained continuously in the root zone also minimize the diurnal depression of plant water potential, thereby minimizing periods of depressed expansive growth (Stegman, 1983).

Fully automated irrigation systems are now available, so that the frequent irrigations required by these systems do not increase labour costs significantly. Under these conditions, the need for defining a critical level of water depletion, and hence timing of irrigation, becomes redundant, and only decisions on the right amount of water to apply remain relevant. With high-frequency irrigation, at intervals of one to six days, the amounts required to meet current evaporative demand are applied, and these can be determined by monitoring the weather (Hillel, 1987); leaching requirements will be treated separately.

It should be clear that the discussion on irrigation scheduling therefore refers almost entirely to the irrigation methods, in which the root zone passes through successive cycles of wetting and drying. In these methods, the soil serves as a reservoir for water, permitting relatively long intervals between irrigations.

The soil is saturated during and immediately after irrigation, soon thereafter soil moisture content reaches field capacity, which approximates an ideal condition for plant growth. Follows a period of gradual soil water depletion, during which moisture stress increases, and a critical point is reached at which growth and yields are affected; the plant continues to extract water until the permanent wilting point is reached.

Optimal moisture conditions for plants obtain only during a fraction of each cycle, and the plants are submitted most of the time to a gradually increasing soil moisture tension, until the next irrigation, when the cycle begins anew. Under these conditions, shorter or longer periods of water stress are almost inevitable, usually causing adverse effects on crop productivity.

Efficient farm use of water for irrigation implies preventing moisture stress in the root zone from reaching a level at which the yield or quality of the marketable crop is adversely affected, i.e., proper irrigation scheduling. For this, two major decisions are required: irrigation *timing* and *amount*. These two decisions are not independent of each other (English et al., 1980).

Concepts

Critical moisture stress. One can consider, as the optimum soil moisture content of the root zone, the range of moisture fluctuating between field capacity (as the upper

limit) and the soil moisture tension level at which the yield of the marketable product is reduced (as the lower limit). This can be termed the 'critical soil moisture tension' (Fig. 12.7).

The critical soil moisture tension will depend on the nature of the crop and, in particular, on the effect of soil moisture stress on the marketable product.

The differential response of crops to water stress at different stages of growth has been discussed in Ch. 4; for the 'critical soil moisture tension' is not a constant throughout the growing period even for a given crop. Adjusting irrigation schedules in accordance with the critical periods of growth, so as to prevent soil moisture tension from exceeding the critical level, has a considerable bearing on yields as well as on total water requirements. There is a general tendency in farming practice to over-irrigate the crop in its vegetative growth stages, and to underestimate water requirements at periods of maximum susceptibility to water deficits – namely, when the plant is flowering and fruiting. Over-irrigation during the later stages of growth will usually cause a delay in maturity, without necessarily improving yields.

Reliable information on optimum soil moisture content for each crop can only be obtained on the basis of field experiments in which the reaction of each crop to different soil moisture régimes is determined.

Integrated moisture stress. Taylor (1952) suggested that the soil moisture régime cannot be described adequately by indicating the soil moisture content at the time of irrigation of a specified soil layer. He proposed that the whole distribution of local and temporal moisture states, at all depths throughout the root zone and throughout the growing period, should be taken into account. Taylor therefore proposes an index called 'integrated moisture stress' (IMS) to integrate all the local and instantaneous moisture tension values over the relevant soil profile and the growth period.

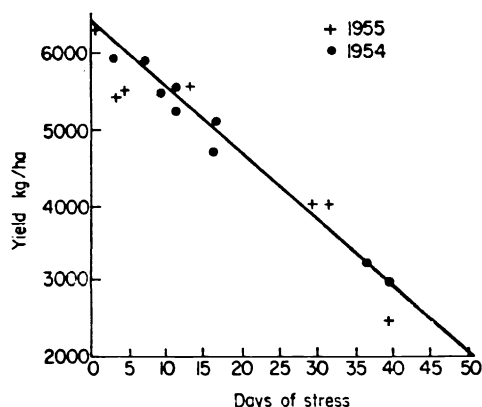


Fig. 12.7. Relationship between grain yields of maize and the number of days of critical soil moisture tension (soil moisture below 12% on a loess soil). From Bielora and Rubin (1957).

Yield responses to critical moisture stress. Crop responses to soil water availability have been discussed in detail in Ch. 4. Here we will mention only those aspects that are directly relevant to irrigation scheduling.

For many years, the view prevailed that soil moisture is equally available to plants over the whole range from field capacity to the permanent wilting point (Veihmeyer and Hendrickson, 1927).

This view prevailed uncontested for quite a number of years, and led to the generally accepted procedure of withholding irrigation until soil moisture was very near or at wilting point, and then applying the full amount of water required to fill the entire root zone to field capacity.

The numerous empirical field studies on a variety of crops and soils carried out subsequently, generally disproved the above mentioned assumption. In a review of 80 research papers dealing with crop response to soil moisture régimes, the growth of crops and their yields was found to respond to differences in soil moisture levels within the available range in 66 cases; in most cases yields declined as moisture stress increased (Stanhill, 1957).

Hagan (1957) postulated that crop-yield responses to soil moisture depletion fall into three categories (Fig. 12.8):

(a) Crops for which water is equally available over the entire available moisture range during each irrigation, so that no appreciable yield increases are obtained by irrigating before soil water potential falls to near -15 bar. These are generally tree crops, with very extensive and deep root systems, which continue to withdraw water from deeper layers, after the layers which are sampled for soil moisture content have reached wilting point. The lack of crop response to declining soil water potential is therefore more apparent than real.

(b) Crops whose yields diminish as soil water stress begins to increase rapidly.

(c) Crops whose growth and yields decline progressively as soil moisture stress increases and for which high moisture stress values, even for brief periods, have a considerable depressive effect on crop yields (Fig. 12.9).

To these three groups, it is possible to add a fourth category, i.e., crop plants whose economic yield increases under water stress. These are generally crop plants in which the economic yield is a chemical that is produced in response to stress (alkaloids, sugars, latex, etc.) (Fig. 12.10).

Figs. 12.9 and 12.10 illustrate with specific examples the differential effects of irrigation on different components of biological yield. In Fig. 12.9, the optimum moisture levels for seed production in Ladino clover are markedly different to those for forage production; in Fig. 12.10 the critical moisture supply for optimal sugar production is significantly lower than for root and foliage production.

Turner (1990) points out that there are situations in which plant water deficits can increase yields and/or water use efficiency. For example, in cotton, weekly irrigations, instead of every two weeks, did not increase yield, but caused shedding of

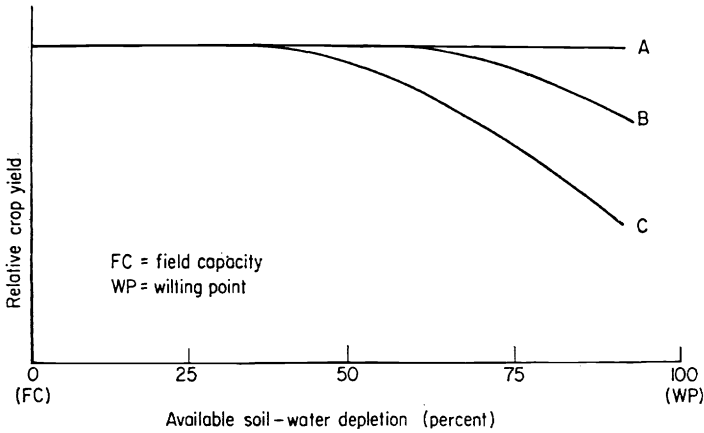


Fig. 12.8. Various typical crop-yield responses to soil moisture depletion. The three curves represent, respectively, (A) cases where moisture is equally available over the entire available moisture range during each irrigation cycle, so that no appreciable yield increases are obtained by irrigating before soil moisture content falls to near wilting point; (B) cases where yields diminish as soil moisture stress begins to increase rapidly; (C) cases in which high moisture stress values, even during brief time intervals, have considerable effect on crop response. From Hagan (1957). By permission of California Agriculture.

young bolls, due to competition for assimilates between young leaves and stems and the developing flowers. The weekly irrigation prevented slight stress from occurring, but delayed the onset of fruit set; as a result, water use efficiency was halved, the growing season lengthened and the costs of water and insect control increased.

To maximize crop productivity, soil water within the root zone must be kept between an upper limit, to ensure an adequate diffusion rate of oxygen to the roots; and a lower limit, to ensure that the unsaturated hydraulic conductivity of the soil is adequate for water and nutrient uptake (Phene, 1974). These limits are dynamic, varying with changes in root development and other factors, and are therefore difficult to determine (Smith et al., 1982).

To keep soil water between these two levels throughout the lifetime of a crop, the quantity, frequency of application, and placement of water must be controllable. In most irrigation systems, the upper level is exceeded for an appreciable time after each water application, leading to soil anaerobis through transient waterlogging; the frequent irrigations required to remain above the lower level are too costly in labour, and also increase the time during which the upper level is exceeded. Hence, the traditional tendency in irrigation has been to reduce the number of irrigations to the minimum possible by (a) waiting until available soil water is depleted almost entirely, and (b) replenishing with the full amount required to refill the root zone to field capacity.

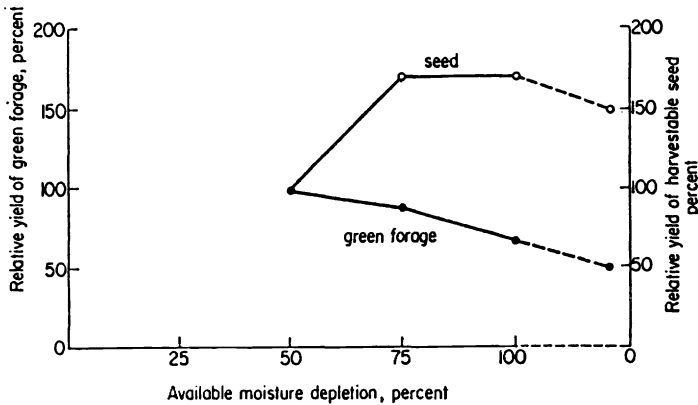


Fig. 12.9. Response of seed yield and vegetative dry-weight of Ladino clover to soil potential. Note that slight stress improves seed yield whilst forage yields decline with increasing moisture stress. From Hagan (1957). By permission of California Agriculture.

The optimizing approach. Traditionally, it has generally been accepted that the volume of irrigation water should be closely related to evapotranspiration, and the water deficit replenished throughout the root zone (Israelsen and Hansen, 1967).

Numerous studies have shown that it is possible to deplete available water to certain levels – which depend on the crop, climate, soil type (Gregory, 1990), the economic marketable product, and the root-zone depth – (Jensen et al., 1967) before the yield or quality of the marketable product is affected.

Some workers have adopted the term ‘extractable water’ to relate physiological

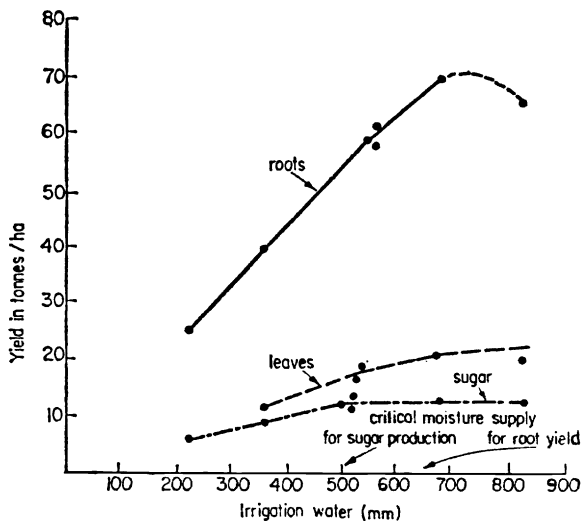


Fig. 12.10. Effect of irrigation on yields of sugar beet tops, roots, and sugar. From Bielora and Rubin (1957).

processes within the plant to the amounts of soil water used (Gregory, 1990).

A great number of studies have attempted to define allowable water depletions (Stegman, 1983). In general, significant yield-reducing stress does not occur until about 65% of the available soil moisture has been depleted (Ritchie, 1981). Plant water potential, diffusive resistance, leaf temperature, and transpiration responses remain quite stable across a wide range of soil moisture levels until only 30–35% remains; then onset of stress is rapid (Kanemasu et al., 1983).

Doorenbos and Kassam (1979) suggest a depletion of 50% as a safe level for a wide array of crops and soils. To make the criterion more flexible, these authors propose a permissible decrease of 30%, in periods of low ET demand (<3 mm/day) or 30% increase when ET demand is high (8 mm/day).

On the basis of these findings, the 'optimizing approach' was developed in a semi-arid area with winter rainfall and dry summer. It was stipulated that irrigation should be supplementary to rain water stored in the root zone. Thus, instead of replenishing the water deficit throughout the root zone, sufficient irrigation water was applied to wet only the soil volume containing 70–80% of the active roots. The deficit was resolved by the crop gradually depleting the water stored during the rainy season.

It was assumed that the optimizing approach would enable a significant saving in irrigation water, with minimal loss in yield. Experience subsequently vindicated the new approach, provided that moisture in the potential root zone was at field capacity at the beginning of the irrigation season. When winter rainfall was inadequate for this purpose, the partial wetting method during the irrigation season resulted in lower yields (Shmueli, 1973).

Deficit irrigation. A similar approach called 'deficit irrigation' was developed in California, by applying less water than the potential evapotranspiration (PET) of the crop, and causing mild stress. In many crops the system was found to optimize yield in relation to water supply. It also reduced the leaching requirement.

This was done by applying an empirically determined fraction of PET, or by lengthening the intervals between irrigations to produce pre-determined levels of soil moisture depletion (Loomis, 1983).

Deficit high-frequency irrigation (DHFI). In experiments conducted at Prosser, Washington, it was found that it is possible to save significant amounts of water, without loss of yield, by irrigating at very frequent intervals with amounts less than ET demand.

The new system would therefore be very attractive in areas in which water is very expensive, limited, or both. Therefore, researchers at Davis, California, conducted experiments on three summer crops, on a deep loam soil, to verify any advantages of DHFI under conditions of limited water supply. The soil was partially dry at the beginning of the experiments, because of drought in the winter preceding the trials (Fereres et al., 1978).

Under the conditions of these experiments, with little water stored in the soil, it was found that frequent light irrigations, at a rate less than ET demand, resulted in substantial reductions in yield; WUE was either unaffected, or even reduced, due to greater losses by evaporation.

It was concluded that in the Prosser experiments, on which the DHFI system was based, ET was met by a combination of water applied *and* depletion of stored soil water. Therefore, there was no actual 'deficit' in the DHFI moisture régime. The authors concluded that if the objective is to optimize WUE by supplying less water than ET, this will be better achieved by storing water in the soil profile, rather than by frequent, light irrigations.

When water supplies are limited, a useful procedure is to wet the full root zone to field capacity before planting, and then to irrigate the crop at sensitive growth stages. This approach has the advantage that it promotes root growth deep within the profile. The most favourable conditions for root growth are provided when conditions throughout the root zone are moist, but not excessively wet, and when there is a gradual depletion of moisture of the surface layers (Kanemasu et al., 1983).

Wide-spaced furrows. Another approach which attempts to make significant water savings without adversely affecting yields is the use of wide-spaced furrows (Stone et al., 1982). The method can be operated by irrigating alternate furrows in a conventional system. Early studies of the method had found that this method entailed significant yield reductions when severe evaporative conditions prevailed during the late vegetative and fruiting stages. It was subsequently shown that these yield reductions could be avoided by (a) ensuring that the water moves through the furrows at least as fast as for conventional furrow irrigation, and (b) substituting wide-spaced furrow irrigation by every-furrow irrigation during the critical period in a high-stress season.

Wide-spaced furrow irrigation was found to reduce water requirements by 20–50%. The authors suggest that the benefit is due to reduced non-productive evaporative losses. Though not conclusively, no trend was apparent that mining water against the water available for the next season was involved.

Determining when to irrigate

Irrigation scheduling is usually based on soil water measurements, plant indicators, soil moisture accounting, or various combinations of these approaches.

Soil water measurements. The objective of soil moisture monitoring is to determine "when water reserves have been depleted to some level predetermined to serve as the minimum allowable level" (i.e., the "time to refill criterion" (Hillel, 1987)). Soil-based irrigation scheduling is "a relatively simple feedback network, and the limit to its operation has been in the monitoring and interpretation phase" (Topp and Davis, 1985).

Soil water potential can be estimated either directly, or by moisture balance.

Techniques of soil moisture measurement are:

(1) *Gravimetric sampling methods.* Soil samples are taken from the root zone and dried at 105°C, after which the weight loss is determined. If the specific weight of the soil is known, the percentage of water in relation to soil volume can be calculated.

The main disadvantages of this method are (a) the time-lag of at least 24 hours between sampling and the availability of the results, (b) the need for a large number of samples, and (c) the large amount of labour involved. However, the method is simple and straightforward, does not require expensive equipment, and gives very accurate results.

(2) *Electrical resistance units.* This method is based on the linear relationship between the electrical resistance and moisture content of the soil.

Units that measure electrical resistance, consisting of two electrodes embedded in blocks of suitable porous material – such as gypsum, nylon, or fibreglass – are buried at appropriate depths in the root zone. Equilibrium is established between the soil moisture content and the moisture content within the blocks (which respond to fluctuations in soil moisture). If the blocks have been individually calibrated for the soil type in which they are being used, the electrical resistance within each block can be measured by a Wheatstone bridge and from this the moisture content can be deduced.

The advantages of this method are the relatively low cost of the units, the speed with which readings can be made, and the suitability of the method for automatization in remote reading and recording (Stanhill et al., 1967).

(3) *Tensiometers.* A tensiometer consists of a porous ceramic cup and a pressure gauge. The cup is buried in the soil at the appropriate depth, and equilibrium is established, through the porous material of the cup, between the water in the apparatus and that in the soil. Fluctuations in soil moisture tension are accurately reflected by variations in the pressure gauge.

Tensiometers are effective at a moisture range from saturation to 0.8 atm soil moisture tension, and will therefore encompass moisture fluctuations involving 90% of the available water in sandy soils, but not more than 50% in clay soils. When moisture tension increases beyond 0.8 atm, air penetrates into the porous cup and the whole system becomes ineffective.

In view of the high cost of the tensiometers, they are generally in the zone of maximum soil water withdrawal, and their use is commonly limited to high-value crops for which soil moisture has to be maintained at continuously high levels. The tensiometers can be used to activate the irrigation system.

(4) *Neutron probes.* Equipment based on the use of radioactive materials has been developed for measuring soil moisture (Fig. 12.11).

When fast neutrons collide with the nuclei of hydrogen atoms in the soil, they are transformed into slow neutrons. As water is the main source of hydrogen in the soil, the number of collisions will depend on the soil moisture content of the soil. The number is determined by a slow-neutron counter, the neutron source being lowered

into the soil to the required depth – into special access tubes inserted in the soil. The number of slow neutrons is correlated with the moisture content of the soil.

This method has a number of advantages. The measurements determine moisture content directly in relation to soil volume, and can be expressed as mm of water in relation to soil depth. The moisture determinations are not affected by salt content of the soil at normal field salinity. The method is very accurate and rapid.

The recent improvements of electronics, radioactive source configurations, and instrument portability have made neutron probes practical tools for irrigation scheduling (Gear et al., 1977).

Cassel (1984) summarizes the main advantages and drawbacks of different scheduling techniques in Table 12.2.

(5) *Time-domain reflectometry (TDR)*. This is a technique which can measure the high-frequency electrical properties of materials. In soil applications, TDR measures the dielectric constant. Water has a dielectric constant of 80, contrasting with values of 2 to 5 of soil solids, so that a measure of the dielectric constant of the soil gives a good measure of its water content in the field with an accuracy of 2%. The equipment does not need to be calibrated for different soils. A single measurement, spanning the depth of the root zone, immediately shows the amount of remaining water. A number

List of Symbols

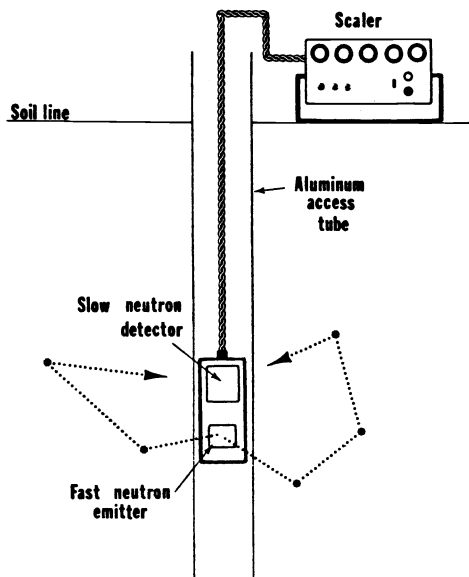


Fig. 12.11. A neutron moderation device used to determine soil water content. The instrument consists (a) of a probe containing a source of fast neutrons and a slow neutron detector, and (b) a scaler which displays the number of slow neutrons detected over a measured period of time. From Thien (1983). Reprinted by permission of John Wiley & Sons, Inc. Copyright © 1983.

of types of TDR instruments are available commercially. Topp and Davis (1985) give a detailed description of the system and its operation.

(6) *Phene and Howell method* for monitoring and scheduling high-frequency irrigation automatically (Phene and Howell, 1984). The soil matrix potential is measured frequently, using the principle of heat dissipation in a porous ceramic block or disk in contact with the soil. The voltage output of the sensor increases with dryness of the soil. Once the sensor is calibrated, its measurements are independent of soil texture, temperature, and salinity and can be used in any soil to monitor soil moisture and to control irrigation automatically (Phene et al., 1985).

Plant indicators. The various methods of scheduling irrigation based on soil water status described in the previous section cannot overcome a basic difficulty, namely that of determining the water deficit *as perceived by the plant*.

Turner (1990), on the basis of various studies, suggests that soil water status may even not be a reliable indicator of plant activity and that plant water status or the physiological activity of the plant may be a more reliable indicator for scheduling irrigation than soil water status.

Plant indicators can be useful for irrigation scheduling, provided they are simple to measure and show visible changes before the plants have been harmed by water stress.

The possibility of using the actual plant, which integrates all the factors involved in determining its own water status – soil conditions, atmospheric conditions, and plant characteristics – has been extensively studied and a number of methods have been proposed that are based on physiological indicators of water needs. Physiologi-

TABLE 12.2

The initial cost, ease of use, labor requirement, and degree of reliability for seven irrigation scheduling techniques.

Method	Initial cost	Ease of use	Labour requirement	Reliability of information
Feel	very low	easy	low to medium	generally low
Gravimetric sampling	low	difficult	high	high
Neutron meter	high	medium	medium	high
Tensiometer	low	easy	medium	high
Electrical resistance blocks	medium	medium	high	high
Checkbook	low to high	medium to difficult	low to high	medium to high
Infrared thermometer	high	easy	low	?

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cal techniques use plant measurements, such as stomatal resistance, leaf water potential, rate of growth, or canopy temperature.

One drawback of this approach is that plant responses are the result of many physiological processes, each of which may be affected differently by water deficits (Vaadia and Waisel, 1967). From a review of the considerable literature already available at that time, the authors concluded that the results of research on effects of water deficits on physiological processes were “fraught with ambiguities, contradictions, and a lack of basic information”.

(1) *Visual methods.* An adverse water balance is soon reflected in the appearance of the plant. Transient wilting of the plants at certain hours of the day are the first signs of an incipient imbalance in water supply. Delaying irrigation until wilting becomes more severe will usually affect crop yields adversely (Fig. 12.12). Fortunately, water stress does not usually occur at once in the whole field, but appears first in patches; this gives some advance warning of impending water need.

Another approach is to grow, in the field, ‘indicator plants’ which are more sensitive to moisture stress than is the main crop, so that indications of the impending need for irrigation are given before the crop suffers a setback due to lack of available moisture (Haise and Hagan, 1967).

Leaf rolling in many grasses and cereals is sensitive to leaf water status beyond a threshold value and is used as a rating score for selecting for drought resistance in sorghum (cf. p. 237).

A leaf rolling index has been proposed as an indicator for irrigation scheduling; the index is the width of the rolled leaf as a fraction of the unrolled width at the point of maximum leaf width (Begg, 1980).

Colour of the foliage. Most farmers are aware of the fact that with increasing moisture stress, the leaves of most crops change colour – from the bright green of well-watered plants to the dark green typical of water-stressed plants. In this case, too, isolated patches of dark-green plants may give advance warning of soil moisture stress. Yet nitrogen application, which also affects leaf colour, may make it difficult to use this characteristic as an indicator of water stress.

Rate of growth. Growth depends first and foremost on turgor, which in turn is dependent on a favourable water balance. Plants are so sensitive to the internal water balance, that daily fluctuations in the moisture content of the plant tissues are reflected in parallel fluctuations in the growth rate of expanding organs.

Stalk elongation is markedly reduced when soil moisture stress approaches the critical level, but accelerates again after irrigation. Criteria can be developed for different crops. For example, in cotton the rate of elongation of the internodal space below the growing tip can serve as a physiological indicator of water stress. In a moderately fertile soil, it was found that a rate of elongation of 0.5 to 1 cm daily of the internodal space indicated the approach of a critical soil moisture tension and the need for irrigation (Aharoni, 1964).



Fig. 12.12. Maize plants suffering from a deficiency of moisture. At this stage of severe moisture stress, visual symptoms are no longer useful for irrigation scheduling, as irrigation at this time will not prevent an appreciable reduction in yield. By courtesy of O.A. Lorenz, College of Agriculture, Davis, California.

(2) *Water potential of the plant.* Soil moisture tension is reflected in the moisture content of the plant tissues and in their osmotic potential. Many attempts have been made to develop simple and practical techniques, based on this relationship, that could serve for the timing of irrigations. Determining the concentration of solids in the plant sap by use of a refractometer, and measuring the electrical resistance of the sap with a Wheatstone bridge, are examples.

The most widely used technique for measuring the water potential of the plant in the field is the *pressure chamber* (Turner, 1990). The data obtained are referred to as 'xylem pressure potential' (Ritchie and Hinckley, 1975) or total leaf water potential (Stegman, 1983). Another useful technique is the thermocouple psychrometer (Boyer, 1987).

Though leaf water potential is the driving force for plant transpiration, measuring leaf water status has the disadvantage that it is not necessarily a good measure of the physiological or metabolic activities of the plant (Turner, 1990). Additionally, osmotic adjustment enables the plant to adapt to gradually developing water deficits, thereby changing the water potential at which physiological activity is adversely affected (cf. p. 241).

(3) *Stomatal conductance.* In many crop plants the degree of closure of the stomata

is a sensitive indicator of plant water status. It is widely recognized that the stomata do not respond to changes in leaf water potential until a critical threshold level is reached (Begg and Turner, 1976).

However, even before the threshold is reached, a reduction in crop yield may result from other physiological or morphological processes being affected by water stress (Vaux and Pruitt, 1983). For example, stress may be too mild to close stomata and thereby affect photosynthesis directly, but may be great enough to affect growth; the reduced leaf area would limit leaf area and light interception. This effect is irreversible, in contrast to the direct influence on photosynthesis of stomatal closure, which is transient.

A further limitation in the use of stomatal behaviour as an indicator of a critical water status threshold is that stomata are also sensitive to light, and the method is therefore difficult to use on cloudy days (Turner, 1990).

Various methods have been developed for rapidly and accurately measuring stomatal opening under field conditions, as a diagnostic tool for predicting the timing of irrigation. The following are noteworthy:

(a) *Infiltration methods.* These measure the rate of infiltration into the leaf tissues of liquids with low viscosity; the rate of infiltration reflects the size of the stomatal aperture which, in turn, depends on the water supply to the plant. A mixture of paraffin oil and turpentine has given good results in cotton (Shmueli, 1964). As can be seen in Fig. 12.13, the rate of infiltration of the mixture used remains fairly constant until the plant becomes stressed, approximately after 60% of the available moisture in the 0–90 cm soil layer has been exhausted. The method is reliable only if standardized procedures are adopted, such as using leaves of a similar age, and carrying out the tests on a predetermined region of the leaf, under certain conditions of light intensity, and at a given hour of the day. The method is simple, does not require expensive equipment, and gives an accurate estimate of soil water tension, enabling timing of irrigation that ensures high yields. The main drawbacks of the method are the need for experienced operators in order to obtain objective results, and the fact that the method is suitable only during certain periods of plant development.

(b) *Field porometers.* These measure the degree of resistance to airflow through the leaf, on the assumption that the rate of resistance will be closely related to the degree of opening of the stomatal apertures. Special forms of equipment have been developed for this purpose, called porometers. These consist of a receptacle containing air under pressure, an apparatus for forcing the air through the leaf, and a gauge for measuring the resistance to the airflow (Shimshi, 1965). The method is limited to crops which have stomata on both sides of the leaf; an increase in resistance to airflow, during noon hours, is an indication that soil moisture stress is approaching a critical level.

Since the 1970's, there has been a surge in the development of porometers of various designs which provide reliable measurement of stomatal resistance (Sharma, 1985).

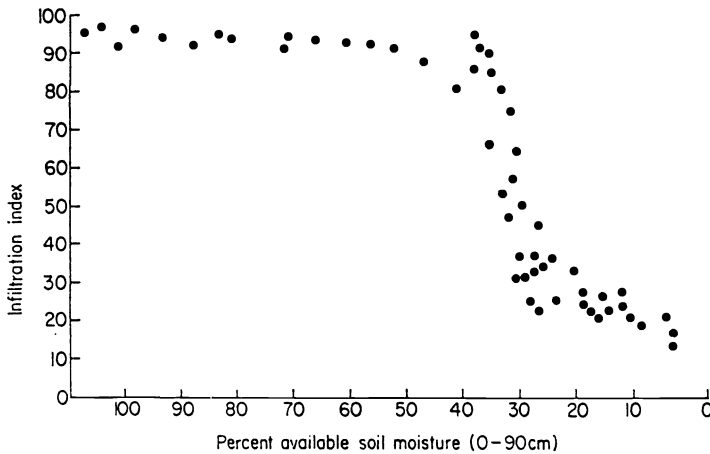


Fig. 12.13. Relationship between infiltration index in cotton leaves and available soil moisture. The tests were made between 12.30 and 13.30. From Shmueli (1964). By permission of the author.

(4) *Canopy temperature.* The use of foliage–air temperature differences as a timing method for irrigation is based on the rise in plant temperature due to water stress, as reduced transpiration dissipates less of the incoming solar radiation (Stegman, 1983).

Canopy temperatures can provide a good measure of crop water status if certain factors are taken into account (Jackson, 1982). Canopy temperature can be measured remotely by infrared thermometers held in the hand or mounted above the plant canopy (Johnson, 1987). The measurements are taken in the early afternoon (13.00 to 14.00) at the time of maximum surface temperature (Stegman, 1983).

The major drawback of the technique is that it is difficult to use on windy or partly cloudy days, inducing stomata to open and close intermittently (Turner, 1990).

Soil moisture accounting. The so-called book-keeping or water-budget procedures are based on the use of daily soil water balances, in which the amounts of water added to the soil by precipitation or irrigation are balanced with the losses due to evapotranspiration. The objective of this approach is to provide reliable information enabling scheduling of irrigation on a fairly wide irrigated tract, without having to rely on direct soil moisture measurements on individual farms.

Water balance models. The availability of computers has made water balance methods applicable on a wide scale; high efficiencies are attainable with these models, i.e., near-maximum yield with minimal annual irrigation application (Stegman, 1983).

These methods require information on initial soil moisture, WHC of the root zone, and other crop and soil characteristics as initialization inputs. Daily climatic varia-

bles, irrigation dates and amounts of water applied are required throughout the growing season (Kanemasu et al., 1983).

The soil water balances can be defined as:

$$\text{SMB} = \text{SM} + \text{Pe} + I - D - \text{ET},$$

in which SMB is the soil moisture on a given day, SM is initial soil water, Pe is the effective precipitation, I is irrigation, D is drainage below the root zone, and ET is evapotranspiration (Kanemasu et al., 1983).

The models produce running estimates of prevailing soil moisture depletion; irrigations are scheduled at times when SMB approaches an allowable depletion limit as determined by appropriate criteria (Stegman, 1983).

'Bookkeeping' procedures for scheduling irrigation applications have been developed and successfully applied in a number of places (Van Bavel, 1960). These methods are applied on a community service basis, with a central office serving a major irrigation project or district having uniform climatic conditions. Data on evapotranspiration, derived from evaporation installations located in a number of representative sites, are conveyed to the central office, where the calculations on moisture use are made, employing the appropriate crop coefficients. This information is then conveyed to the irrigators in the district by phone, radio, television, newspaper, or any other appropriate means of communication.

The general moisture content of the soil at the beginning of the irrigation period, as determined by random sampling for each district, serves as the basic starting point for the moisture record of the irrigation season. Evaporation values are converted into weekly water use based on water use curves, established experimentally for the crops grown in the area. These are subtracted from the base starting point, whilst precipitation is added. Irrigation requirements as well as the anticipated time of irrigation are then forecast. These recommendations take into account the water-holding capacities and readily available moisture values as determined for the major soils of the district (Steed, 1967).

The bookkeeping methods for scheduling irrigation have been most successful in humid regions, because occasional heavy rains cancel the cumulative errors that may have been made in estimating the water used, and permit 'a new start' to be made several times during the season. In arid regions the cumulative errors have, up to the present, made the method very problematical (Phelan, 1964).

Simulation water budget models. Climatological models have been developed using various parameters which are simple or complex. The simple models have the advantage of ease of use and economy of input data; however, "Highly simplified models frequently cannot answer the questions of interest. Moreover, they often require recalibration for each new application or site" (Boote and Jones, 1988).

Complex modelling techniques can be excellent research tools, but their large data

requirements strongly limit their use as management tools (Chopart and Vauclin, 1990).

Overall, the incompleteness of knowledge regarding the parameters required, the complexities of the technologies and of the models themselves, and the need for intensive multidisciplinary effort, are barriers to the use of simulation, and there are few examples of its successful application (Swindale, 1989). This view is supported by Vaux and Pruitt (1983) who state that “despite the substantial body of knowledge available on crop–water relations, knowledge is not so complete that a grower can engage in moisture stressing with complete certainty as to what the results will be”.

Estimating potential evapotranspiration (PET). All water budgeting methods require estimates of PET. A number of formulas have been developed for this purpose on the basis of physical and meteorological data. The accuracy in estimating PET is a major factor enabling economy in water use.

(1) *Evapotranspiration.** Evapotranspiration (ET) includes evaporation of liquid or solid water from soil and plant surfaces (intercepted water, dew fall) plus transpiration of water through plant tissues expressed as latent heat transfer per unit area or its equivalent depth of water per unit area (Burman et al., 1983).

For ET to occur, water has to be available at the evaporative surface and sufficient energy must be available to vaporize the water. For the process to continue, the humidified air must be transported away from the transpiring surface. The evaporative demand is controlled by meteorological factors, while the supply of water is influenced by meteorological, plant and soil factors (Sharma, 1985).

(2) *Potential evapotranspiration.* Potential evapotranspiration (PET) defines the upper limit of the evaporation rate from a given soil-vegetation unit under a given set of meteorological conditions (Sharma, 1985). There are many definitions of PET in the literature, and a number of formulas and techniques for quantifying PET.

The use of PET has been replaced by many authors by the term reference ET (ET_R) specifying ET from either lucerne or short grass. ET_R is the maximum ET which can be expected from the reference crop under the prevailing meteorological conditions (Cuenca and Amegée, 1987).

The use of lucerne, instead of the more frequently used short grass sward, has the advantage that the former is aerodynamically rough, like many field crops, and therefore its ET reaches the maximum possible for a crop in a particular location (Jensen et al., 1971).

The rapid advances in electronic technology, combined with worldwide research into the Penman equation, has enabled the correct calculation of reference crop ET from weather data collected from automatic weather stations (Burman et al., 1983).

*Monteith (1985) objects to the term ‘evapotranspiration’ which he considers unnecessary and inappropriate. He suggests using the term ‘total evaporation’ (TE) when emphasizing that the loss of water from soil and vegetation occur together.

Calculating the energy balance. This method of calculating potential evapotranspiration is based on the assumption that as transpiration is, in effect, the evaporation of water from the surface of a plant, transpiration rates are controlled by the same physical factors as those which control evaporation. Therefore, fundamentally, evapotranspiration can be considered as a physical phenomenon which requires energy to supply the heat of vaporization that is necessary for the process (Penman, 1948).

In addition, evapotranspiration can only take place when the atmosphere is not completely saturated; it is therefore dependent on a mechanism that will move water vapour from moist to drier levels in the atmosphere.

The principal factors affecting evapotranspiration are air temperature, atmospheric humidity, and cloudiness, whilst differences in reflection from the soil surface or plant cover are of minor importance. As a result, the rate of water loss from an actively growing short green crop that completely shades the ground, when water is non-limiting, is about the same as that from a free water surface, being accordingly equal to PET (Penman, 1952).

Within certain limits, therefore, PET is independent of the type of crop or kind of soil on which the crop is growing, and is primarily determined by the prevailing weather. In consequence, according to Penman (1956) there should be no effective differences in water consumption of different irrigated crops at a given time and place, water consumption being dependent on the available energy.

By using the appropriate meteorological and aerodynamic data, Penman has established a formula for calculating the energy balance, and deduces therefrom the values for PET (Penman, 1948).

Empirical formulae based on meteorological data. A number of empirical formulae have been established for calculating PET, based on the following assumptions: (a) that there is a direct correlation between seasonal water requirement and temperature, daylength, and length of the growing period, and (b) that it is possible to disregard other climatological factors, such as wind velocity and direction, relative air humidity, light intensity, etc.

There is no doubt that the last-named factors influence the water requirement of crops. However, in attempting to establish a relatively simple formula, which would be practical and easy for determining water requirements, it was decided to use a minimum number of meteorological factors on which data are readily available.

Blaney and Criddle (1962) were of the opinion that the water requirements of different crops are not identical, even under conditions of identical temperature and daylength. They proposed to determine experimentally an empirical coefficient K , which would be specific for each crop. The Blaney–Criddle formula for determining water requirement is:

$$U = K \times F,$$

where U is the consumptive use of the crop (or ET) in inches for any period, K is the

empirical coefficient, and F is the sum of monthly consumptive-use factors for the period (f): $f = t \times p$, where f = monthly consumptive-use factor, t = mean monthly temperature, and p = monthly percentage of daytime hours of the year. Computations of K for irrigated crops in arid and semi-arid areas have been found to be as follows: lucerne, 0.85; maize, 0.80; cotton, 0.65; pasture, 0.75; and rice, 1.20.

The Blaney–Criddle method is the most widely used method of estimating ET using temperature data. Its popularity is due to its simplicity: if suitable coefficients are available, only temperature and daylength data are needed (Burman et al., 1983). In the modification of the Blaney–Criddle method introduced by the US Soil Conservation Service, the only input required is temperature; all other data required being available in tabulated form as a function of latitude and time of year (Cuenca and Amegée, 1987).

Jensen (1974) stresses that no single method to compute ET using meteorological data can be satisfactory for all climatic regions without local calibration.

(3) *Equipment for estimating PET*. The most commonly used apparatus for estimating PET is the *class-A evaporation pan*, from which water losses are recorded daily.

Pans are inexpensive, easy to maintain, and simple to operate. However, in dry climates, care must be taken in relating evaporation from pans to actual ET (Blad, 1983). PET and evaporation from pans are affected by the same meteorological factors and there is a strong correlation between them. However, the smooth water surface of the pan will evaporate at a lower rate than a rough crop surface, and changes in wind speed will affect evaporation from the crop surface more effectively than from the pan surface (Fuchs, 1973). Therefore pans may give too low estimates of PET and it is necessary to establish experimentally the relationship between pan evaporation and PET for different crops in a given environment. The exposure of the pans also affects the relation between PET and pan evaporation; the values were found to vary from 0.6 to 2.0. The larger values generally occurred when the pans were placed in a partly shaded site or inside an irrigated field (Fuchs, 1973).

Lysimeters are soil tanks especially designed for growing crops under what are essentially field conditions, the soil being kept at or near field capacity; water loss can be measured directly by periodical weighing of the apparatus.

Chamber techniques are methods in which a sample of a plant or a plant community is encased in a chamber; transpiration is measured by recording changes in the humidity of the air as it passes through the chamber. Various versions of this technique have been developed, they all have in common the drawback that it is impossible to reproduce the natural microclimate within the chamber because of the complex and dynamic nature of temperature, humidity, and particularly the wind profiles. The use of chambers is therefore restricted to measurement of comparative evaporation under the environmental conditions imposed by the chamber (Sharma, 1985).

Tracer techniques are techniques by which the linear velocity of sap flow through the stem of a plant can be measured by labeling it with a soluble compound or

introducing a heat pulse. The rate of transfer of the tracer by the transpiration stream is then measured. The measured velocity must be correlated with independently measured transpiration flux. The system is mainly used for trees (Sharma, 1985).

Atmometers are passive devices, that expose a continuously moist paper or porous ceramic evaporating surface, to the atmosphere. They respond relatively quickly to radiation, wind speed, and the dryness of the air (Blad, 1983).

Fuchs (1973) stresses the need to calibrate locally all the empirical methods using meteorological parameters to determine irrigation requirements.

Comparative value of different methods. “There is no agreement as to which method provides the best ET estimate in comparison with lysimeters” (Hatfield, 1990). An assessment of the comparative value of the different methods for measuring PET was made by Stanhill (1961).

In short it may be said that, whilst the Penman formula gives a proper evaluation of the effect of solar radiation and other factors in computing evapotranspiration, there are only a few stations that are equipped to supply the data required. Thornthwaite's and Blaney and Criddle's formulae are empirical, but they are easy to use and generally give fair approximations.

Work in Israel has shown that there is good agreement between the results of field experiments designed to determine optimum water requirements and the optima calculated according to the Blaney–Criddle formula, as shown in the examples in Table 12.3.

In New Zealand, a relatively good agreement was found between soil moisture as measured by the gravimetric method, and the figure obtained by using the Thornthwaite formula for calculating the day-to-day values of evapotranspiration (Rickard, 1957).

In Washington, it was found that evaporation-tank rates gave a much closer estimate of actual evapotranspiration than either the Blaney and Criddle or the Thornthwaite procedures (Edminster and Van Schilfgaarde, 1955).

In general, it can be said that the reliability of the empirical methods for evaluating potential evapotranspiration increases when the methods are calibrated for each crop in each region (Tanner, 1967). This is necessary because the effective rooting depth and the permissible water-deficit for each crop, as well as soil water retention characteristics, are factors that have to be taken into consideration. In addition, the consid-

TABLE 12.3

Optimum water requirements (mm/growing season) of cotton at two locations in Israel

Location	As found experimentally	Acc. to Blaney–Criddle formula
Negev	780	670–770
Esdraelon Plain	688	683–755

erable advection of energy from unirrigated surroundings (the so-called 'oasis effect') affects the energy balance of each location (Haise and Hagan, 1967).

Estimating the amounts of water to apply

Seasonal water requirement. Bucks et al. (1982) define irrigation water requirement (WR) as "the net amount of water that can be supplied by irrigation to satisfy ET, leaching of salts, and miscellaneous water requirements that are not provided by water stored in the soil or by precipitation that enters the soil". This is expressed by the equation:

$$WR = ET + LR + MR - (P + S),$$

where LR is the leaching requirement, MR are miscellaneous requirements (i.e., for germination, frost protection, plant quality, etc.); P is precipitation and S is water stored in the soil.

Water requirement per irrigation. It is possible to calculate the amount of water required to remedy a water deficit in the root zone. This amount will depend on the depth of the root zone, on the critical soil moisture tension, and on the efficiency of irrigation.

The following formula is used for calculating the amount of water to be applied at each irrigation:

$$d = \frac{10 (WF_e - W_o) SD}{E},$$

where d = mm of water to be applied, WF_e = soil moisture percentage (by weight) at field capacity, W_o = soil moisture percentage (by weight) before irrigation, S = specific weight of the soil, E = irrigation efficiency, and D = depth of the soil layer sampled.

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CHAPTER 13

The Maintenance of a Permanent Irrigation Agriculture

The problem

Breakdown of irrigation agriculture

The oldest cause of failure of an entire agricultural system for technical reasons was the breakdown of large irrigation schemes due to poor drainage, rising water tables and resulting salinization (Darling, 1981).

In view of the breakdown in the past of many civilizations that were based on irrigation agriculture, and the numerous cases of rapid soil deterioration under irrigation in modern times – both in countries with a primitive agriculture and in those with the most advanced technologies – doubts are frequently expressed as to the possibility of maintaining irrigated agriculture permanently.

“Natural dryland ecosystems are inherently unstable and exhibit a potential for dramatic changes which are readily triggered by the sudden appearance of extended areas of irrigated crops” (Kassas, 1977).

Magnitude of the problem

In a worldwide survey of salt-affected soils by Shalhevet and Kamburov (1976), it was found that of the 91 million ha irrigated in 24 countries over 50 million (55%) are affected by salinity. Even the highly modern, sophisticated agriculture of the USA is not immune to salinity problems: Wadleigh (1968) estimated salinity to be an existing problem on about 25% of the irrigated land, and a potential threat to about half the more than 90 million ha under irrigation.

Reasons for breakdown

Irrigation systems can fail for other reasons than salinity; overpumping from coastal aquifers with resulting intrusion of seawater (cf. p. 427), overpumping of aquifers with limited recharge potential, so that water levels drop so low that further pumping

is too costly to be economically justified; unstable or weak governments incapable of maintaining the public works essential for an efficient irrigation system; political strife among countries for water rights, etc. (Darling, 1981).

Experience and research have shown unequivocally that the basic causes of the failure of crop production under irrigation are the combined and related effects of excessive salt accumulation in the root zone and the development of a high water table. Because of the high evaporation rates and low precipitation of the arid regions, many arid soils contain appreciable amounts of salts to start with, and natural drainage in these regions is rarely effective. As the salts generally accumulate in areas of low elevation, and as these are the lands that in their topography are best adapted for irrigation, they are already predisposed to salinity hazards which are then aggravated by irrigation proper.

In principle, soil salinization can be avoided even when the water table is relatively near the soil surface, provided the net flow of water in the profile is downwards (Rawlins, 1981). In practice, it is difficult to maintain downward flow when the water table is high; when the water table is within capillary range of the root zone, the vicious circle is closed: additional salts are added to the root zone by the capillary rise of saline water from the water table, and evaporation of water and deposition of salt are increased. As a result, leaching of excess salts becomes impractical and the inevitable restriction of the root zone precludes normal plant development.

In addition to salts, irrigation water carries silt. The latter can make important contributions to soil fertility of the irrigated lands, but it can also choke reservoirs (cf. p. 425) and canals, and eventually accumulate on the irrigated land to a depth that reduces the natural slope and thereby makes removal of salts more difficult (Rawlins, 1981).

A classic example of the combined effect of salinization and silting on a prosperous irrigation economy is the fate of the Mesopotamian plain of the Tigris and Euphrates rivers in present-day Iraq. An area that once supported an estimated 25 million people now provides subsistence for a fraction of that number. Accumulation of salts in the soil was aggravated by the deposition of silt to a depth of 10 m that clogged natural drainage channels and reduced the slope of the land, leading to a rise of the water table into the root zone. The end result was lowered production, and finally, breakdown of the system (Eckholm, 1976).

Prevention of breakdown

An understanding of the factors involved in the breakdown of irrigated agriculture indicates that this can be prevented by the maintenance of a satisfactory salt balance in the root zone, and appropriate management and upkeep of the irrigation system.

If the amount of rainfall or irrigation is sufficient to leach the salts to a depth from which capillary rise to the root zone is insignificant, a harmless zone of accumulation in the subsoil will result.

Eventually, excess salts have to be removed from the soil by an effective system of leaching and drainage. Where natural drainage is insufficient, or becomes inadequate through the accumulation of silt, artificial drainage becomes essential to maintain the water table below the root zone and to remove excess salts. Where there is little natural slope, providing a sink for the leaching water can be difficult, but permanent irrigated agriculture is impossible without a solution to this problem (Rawlins, 1981).

Sources of salinity (Szabolcs, 1977)

The chemical elements and compounds that make an important contribution to salinization and alkalinization of rocks, soils and waters are the cations: Ca^{2+} , Na^{+} , Mg^{2+} , K^{+} ; and the anions: Cl^{-} , $(\text{SO}_4)^{2-}$, $(\text{HCO}_3)^{-}$, $(\text{SiO}_3)^{2-}$.

Because of the limited precipitation, many salts can accumulate in the soils and waters of the dry regions.

The amounts of salts contributed by rivers vary considerable. Rivers that traverse deserts and semi-deserts, such as the Amu Daria, can carry enormous loads of salts; others, that collect their waters from humid areas such as the Nile, have a relatively low salt content.

The main reservoir of salinity in the dry regions is groundwater. However, as long as the groundwater table is sufficiently low, salts will not be brought to the surface by capillary rise of the water, and even saline groundwaters will not necessarily cause salinization.

A major man-made source of salinization is seepage from irrigation channels, which contributes to the rise of the water table, sometimes more than irrigation itself.

Quality criteria of irrigation water

One of the first and essential steps before considering an irrigation scheme, is to assess the quality of the available irrigation water. Whatever its source, irrigation water always contains impurities, such as dissolved salts, solids in suspension, and pollutants. The amount and nature of these materials, under given environmental, soil, and plant conditions determine the usefulness and relative quality of water (Yaron, 1973).

In general, the shortage of water resources in the dry regions results in a tendency to use water of questionable quality. The quality of water will have a bearing on the type of soil that can be irrigated, the kind of crops it will be possible to grow, and the management techniques and irrigation methods to be adopted.

Classification of irrigation waters

A number of criteria have been proposed by various authors, for assessing water

quality for irrigation. The most widely used classification system is that developed by the US Salinity Laboratory (Bernstein, 1967); certain changes in the concept have occurred since its publication (James et al., 1982).

Without going into details of the various proposed approaches to the classification of irrigation waters according to their quality, certain criteria are generally accepted and can serve to predict the effect of irrigation water on soil and crops under specific conditions.

These proposals are usually based on (a) the total salt content of the water, (b) the sodium content, (c) the sodium carbonate content, (d) the content of phytotoxic substances, (e) suspended materials, and (f) the presence of pollutants (Yaron, 1973).

Total soluble salt content (TSS) or salinity hazard

The early assessments of irrigation water quality were concerned mainly with the concentration of soluble salts in the water, irrespective of their composition. TSS content was expressed in g/l, meq/l, ppm, or as specific electrical conductivity.

The salt content of most irrigation waters ranges from 70 to 3500 ppm (Allison, 1964). Irrigation therefore adds appreciable amounts of salts to the soil, and the resultant salinization may, after a time, jeopardize the permanence of irrigation agriculture.

The principal cations of irrigation water are sodium, calcium, and magnesium, and these are generally present as chlorides, sulphates, and bicarbonates.

Though the total concentration of soluble salts is the most important single criterion of irrigation water, it is generally inadequate in itself to indicate quality, as it makes no distinction between different kinds of salts: some salts are more dangerous than others, and certain salts are even beneficial when not present in excess.

When considered in conjunction with additional criteria described below, waters are classified by the US Salinity Laboratory (Richards, 1954) in four categories based on electrical conductivity values:

- C₁ *Low-salinity water* has an electrical conductivity of less than 250 $\mu\text{mho/cm}$ and can be used safely for irrigation of most crops and on most soils.
- C₂ *Medium-salinity water*, which has an electrical conductivity between 250 and 750 $\mu\text{mho/cm}$, can be used safely, if a moderate amount of leaching is possible, for plants with a moderate salt tolerance.
- C₃ *High-salinity water* in the range of 750 to 2250 $\mu\text{mho/cm}$ can be used only on soils with adequate drainage and for crops with fair salt-tolerance, and provided management practices for salinity control are applied.
- C₄ *Very high-salinity water* can be used only on salt-tolerant crops grown under special circumstances, and with adequate management practices on permeable soils. The electrical conductivity is above 2250 $\mu\text{mho/cm}$. Water classification based on salinity hazard, in relation to the permeability of the soil, is presented in Fig. 13.1 (Fireman and Kraus, 1965).

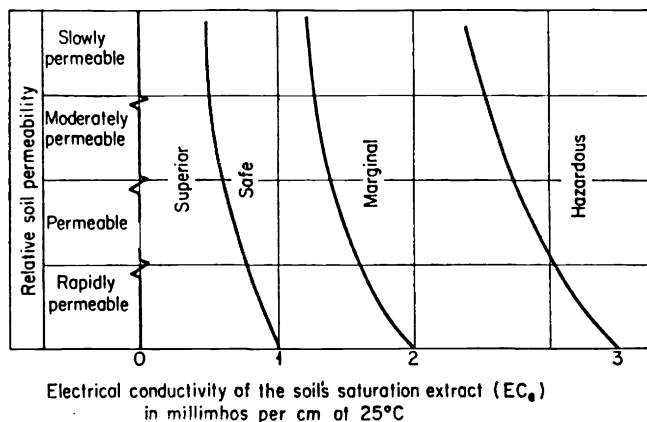


Fig. 13.1. Water classification based on salinity hazard in relation to soil permeability. EC=electrical conductivity of the soils' saturation water extract. From Fireman and Kraus (1965). By permission of Tahal-Water Planning for Israel.

Sodium hazard

In view of the major adverse effects of sodium on the soil and on the crop, its concentration in irrigation water is a major criterion of quality. However, classifying waters on the basis of sodium content alone is not a satisfactory measure of the sodium hazard, as it does not take into account a number of highly relevant factors. For example, the presence of Ca in the irrigation water can alleviate, to some extent, the negative effects of the Na cation – hence the considerable importance of considering the Na–Ca balance in the irrigation water.

Owing to the dynamic equilibrium between soluble and adsorbed ions, the amounts of calcium and magnesium displaced by sodium from the exchange complex of the soil depend on the relative proportions of these ions that are present in the soil solution. Very little calcium will be displaced from the soil exchange complex when sodium and calcium are present in the irrigation water in approximately equal concentrations. When sodium concentration is double or more that of the calcium, however, some of the calcium will be displaced, and with still higher concentrations of sodium, more and more of the calcium will be displaced from the exchange complex.

In the past, the ratio of sodium to calcium was usually expressed in the following formula, called the 'soluble sodium percentage' (SSP):

$$SSP = \frac{\text{soluble Na}^+ \text{ concentration}}{\text{total cation concentration}} \times 100.$$

The determination of SSP is time-consuming, and has been widely replaced by the 'sodium adsorption ratio' (SAR):

$$\text{SAR} = \sqrt{\frac{\text{Na}^+}{\frac{1}{2}(\text{Ca}^{2+} + \text{Mg}^{2+})}}$$

The SAR criterion also has its weaknesses. It is only valid if and when the SAR of irrigation water is approximately the same as the SAR of the soil solution, a situation that rarely occurs under field conditions, for several reasons (James et al., 1982): (a) the concentration of salts in the soil solution increases as the soil dries and therefore varies in time and depth in the profile between irrigations, and (b) salts are added by soil mineral weathering during irrigation, and withdrawn by precipitation.

For these reasons, it is the SAR of the soil solution (SAR_{sw}) rather than the SAR of the irrigation water that affects soil SSP and eventually soil permeability. Consequently, the basic equation for the SAR has been modified to take these factors into account when evaluating the sodic hazard of water (Rhoades, 1968).

An empirical relation of high statistical significance between the SAR of irrigation water and the exchangeable sodium percentage (ESP) of the soil, has been established (Wilcox and Durum, 1967). Therefore, after the SAR value of an irrigation water has been calculated, it is possible to estimate the ESP value of the soil when it is in equilibrium with the irrigation water.

For a rough approximation, the SAR and SSP values are sufficiently similar to be interchangeable at field level, when the exchangeable Na is less than about 40% (James et al., 1982).

Waters may be classified into four categories according to their sodium hazard (Fig. 13.2) (Wilcox, 1958):

- S_1 *Low-sodium water* can be used for most soil types, with no danger of causing salinization.
- S_2 *Medium-sodium water* will not cause difficulties when used on permeable soils with a high sand or organic-matter content. On fine-textured soils with a low calcium content, salinity problems may occur.

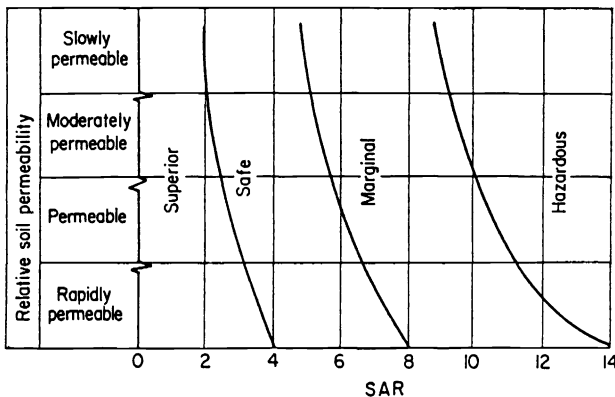


Fig. 13.2. Water classification based on sodium hazard in relation to soil permeability. SAR=sodium absorption ratio. From Fireman and Kraus (1965). By permission of Tahal-Water Planning for Israel.

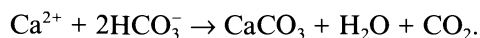
- S₃ *High-sodium water* can cause salinity problems on most types of soil, and can only be used if certain precautions are taken and preventive methods adopted: these include regular leaching, adequate drainage, use of organic manures, etc. If the calcium content of the soil is high, there is little danger of rapid salinization. On soils that are low in calcium, however, the danger of salinization is always imminent, and regular applications of gypsum are indicated.
- S₄ *Very high-sodium water* is generally not suitable for irrigation, and can be used only under exceptional circumstances for special crops.

The dividing points between the above categories depend on the total salinity hazards; with increasing salinity, the permissible SAR values decrease progressively. For example, at EC values of 100 $\mu\text{mho/cm}$ the limits of the various groups are at SAR values of 10, 18 and 26, whereas at 2250 $\mu\text{mho/cm}$ the corresponding SAR values are 4, 9 and 14 (Allison, 1964).

The inherent weakness in rating water into a low, medium, high and very high salinity hazard is that it is too rigid, by not taking into account the crop, soil, and environmental factors that largely determine the degree of salinity of water that can be used safely for irrigation (see next section). Consequently, the water classification described above frequently overestimates the salinity hazard (James et al., 1982). Bernstein (1967) proposed a scheme based on the use of specific factors, in particular salt tolerance of plants (James et al., 1982).

Bicarbonate hazard

Water in which the concentration of the bicarbonates is higher than that of calcium and magnesium together, is unsuitable for irrigation – even if the sodium content is within permissible limits. After each irrigation the Ca^{2+} and Mg^{2+} react with the bicarbonate, and as the soil dries out, they become precipitated as insoluble carbonates, as in the following equation:



With less Ca^{2+} in solution, the relative concentration of sodium in the soil solution, and hence the sodium hazard, increases. Following this process, infiltration rates are reduced, the pH increases, the organic matter in the soil is dissolved, and the soil takes on the typical black colour which is characteristic of soils in which this process is occurring (black alkali). For assessing water quality in relation to its carbonate and bicarbonate content, the residual sodium carbonate (RSC) is calculated (Eaton, 1950) according to the following equation:

$$\text{RSC} = (\text{CO}_3^{2-} + \text{HCO}_3^-) - (\text{Ca}^{2+} + \text{Mg}^{2+})$$

(all expressed in milliequivalents, meq).

When the RSC is less than 1.25 meq/l water quality is considered to be good. With an RSC between 1.25 and 2.50 meq/l the water can still be used for irrigation, pro-

vided essential precautions are taken to avoid salinization Water with more than 2.50 meq/l is not suitable for irrigation (Wilcox et al., 1954).

Water with a given RSC may be dangerous for soils with an alkaline pH, and may have a beneficial effect on soils with an acid pH (Yaron, 1973).

A diagram, combining the various criteria mentioned above for the classification of irrigation waters, is presented in Fig. 13.3.

Chloride hazard

Since the chloride ion has no effect on the physical properties of the soil and is not adsorbed in the soil complex, it has generally been overlooked in water quality classification systems. Because chloride affects certain plants adversely, the prediction of chloride hazard cannot be general, but must be made only for a specific area and specific crop (Yaron, 1973). Most agronomic crops can tolerate up to 5 to 10%, on a dry-weight basis, without developing injury symptoms (Bernstein, 1962).

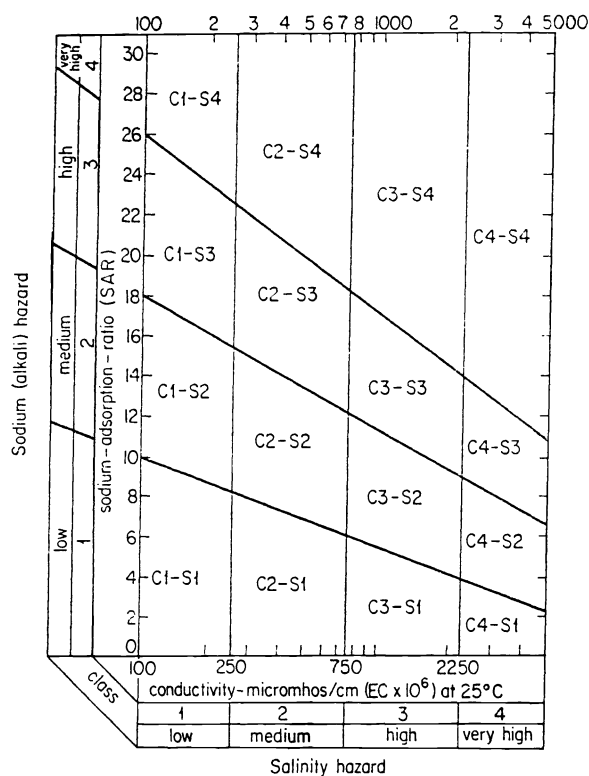


Fig. 13.3. Diagram for the classification of irrigation waters. For explanation, see text. From Richards (1954). By courtesy of the US Department of Agriculture.

Boron hazard

Certain elements, such as boron, which at low concentrations is not harmful to plants, and may even be beneficial, are apt to accumulate in the soil following irrigation and may reach toxic concentrations. Water containing 1 mg/kg of boron can still be considered as safe for most field crops; semi-tolerant crops, such as lima beans, oats, sorghum, wheat, barley, field peas, and cotton, are sensitive to concentrations of 1 to 2 mg/kg, while broad beans, lucerne, and sugar beets, can tolerate concentrations of 2 to 4 mg/kg, which is the upper permissible limit for all crops (Allison, 1964).

Boron is not uncommon in well-water, and a toxic level may be reached in the soil by irrigating with such waters. It may also be present in unusually high amounts in certain soils. Larger quantities of water are required for leaching boron out of the soil than are necessary for sodium salts, as the boron is held more strongly by the soil (Reeve et al., 1955).

Biocide hazard

Irrigation water may contain pollutants from municipal, industrial, and agricultural wastes. Among these are various oily substances, phenols, synthetic detergents, dissolved gases, and agrochemicals. The problem occurs mainly when irrigation return flow is used. Detailed information on permissible levels of these pollutants, together with information on treatment, rate of application, and estimated concentration in the field or the crop can be found in USDI (1968).

Suspended inorganic and organic materials

The silt content of some river waters that are used for irrigation is an important qualitative characteristic. The more clay aggregates and organic matter the silt contains, the higher is its value in adding fertility to the soil. However, sediment-laden water is more difficult than clear water to use for irrigation: water penetration is impaired by the sediment, and such water cannot be used for overhead irrigation without prior sedimentation.

General appreciation of water quality

The suitability or otherwise of water for irrigation cannot be determined without reference to the soil to be irrigated, the crops to be grown, the agronomic practices adopted, and the environmental conditions prevailing in the region. Therefore, quality criteria for irrigation waters cannot be applied rigidly, and will frequently have to be adapted to regional conditions. Even good-quality water can cause damage when applied to an impermeable soil, while poor-quality water may be satisfactory when used for irrigating permeable, well-drained soils (Bernstein, 1962). Two aspects of the problem should be considered:

In relation to crops

The evaluation of irrigation water will depend on the tolerance of the crops to be grown in the rotation, to total salinity and to specific ion concentrations.

Crops differ in their tolerance to soil salinity. The response to salinity of most economic crops has been determined on the basis of measurements of the electrical conductivity of a saturation extract of the soil. The degree of soil salinity at which a specific reduction in crop yield occurs, in comparison with the non-saline condition, serves as a criterion for establishing the relative tolerance of crops to salinity. Various levels of yield reduction have been used, such as 10 to 15% by Bernstein (1962) and 50% by Richards (1954).

The salt tolerance of various field and forage crops is shown in Fig. 13.4.

In relation to soil types

The effect of salts in irrigated soils on plant growth is not determined by the salt content of the irrigation water per se, but depends on the maximum concentration of the salts in the soil solution, which is reached shortly before irrigation.

In very permeable soils, the differences between the concentration of salts in the soil solution and the salt-content of the irrigation water are usually small. In less permeable soils, the concentration of salts in the soil solution, shortly before irrigation, may be ten times as high as in the irrigation water. Therefore, the less permeable the soil, the greater will be the danger of using water with a high salt or a high sodium

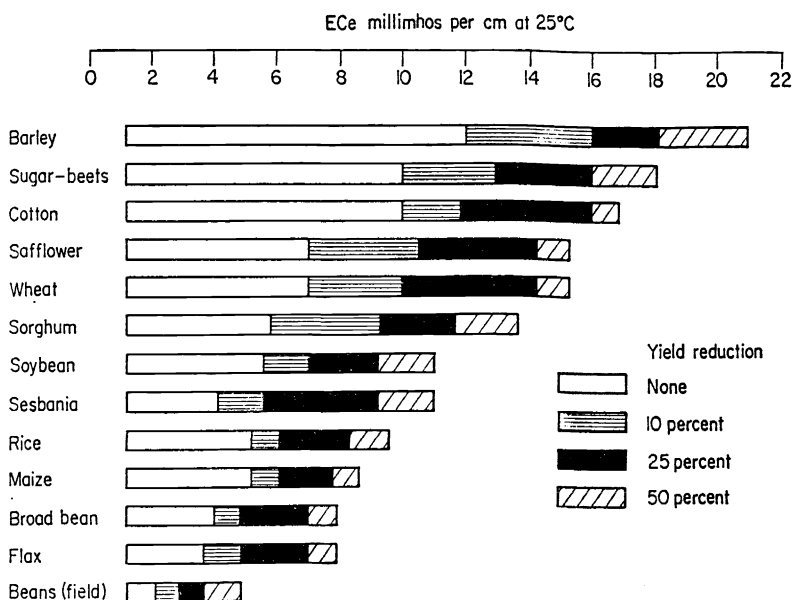


Fig. 13.4. Salt tolerance of a number of field crops. From Bernstein (1962). By courtesy of the US Department of Agriculture.

content. Furthermore, the situation usually deteriorates progressively, as percolation gradually becomes reduced following the replacement of calcium by sodium in the exchange complex of the soil.

In India it has also been found that the higher the pH of the soil is, the narrower will be the range of tolerance to salinity (Agarwal and Yadav, 1956).

James et al. (1982) point out that sensitive crops suffer from SSP values that do not affect the physical properties of the soil; as the SSP increases, the more tolerant crops are affected by poor soil conditions and unbalanced nutrition. Water applied by sprinklers may cause sodium or chloride damage even with water that has no adverse effect on the soil.

Rainfall and temperature

The level of salts that can be tolerated in irrigation water is directly related to the amount of precipitation. In low-rainfall regions or seasons, there is an increased demand for irrigation water, so that more salts are added to soil and at the same time leaching by rain is reduced. These effects are further enhanced by high temperatures which cause increased evapotranspiration. In regions with a high seasonal rainfall, most of the salts that accumulate in the root zone during the irrigation season can be leached out during the rainy season, providing that drainage – whether natural or artificial – is adequate. It is estimated that an annual rainfall of 400 to 500 mm completely removes any excess of salts (Tames, 1950). Consequently, the dangers of salinization will increase, the more arid the region is.

Seasonal variations

The quality of irrigation water is not static, but shows seasonal variation. As a result of evaporation, the salt content may rise in reservoirs as the summer advances. This rise is also a function of the size of the body of water, varying from 20% for a large reservoir such as Lake Tiberias, to 100% in small marshes (Kovda et al., 1967b). The salt content of flowing water may also vary within wide limits. During the flood stage, Nile water has a low salt content and sodium percentage; the salt content is more than doubled at the low-water stage (Bernstein, 1962). Deep groundwater tables generally do not show seasonal fluctuations in salt content. By contrast, rainfall and irrigation may cause considerable changes in the salt content of high groundwater.

Amounts of water applied, and drainage

The soil solution usually has a salt concentration that is in excess of that in most waters used for irrigation. In most irrigated soils the salt concentration of the soil solution is generally from three to ten times as great as that of the irrigation water used (Tison, 1961). This relationship is affected by the actual concentration of salts in the irrigation water and in the soil, by the permeability of the soil, by the efficacy of drainage, by the climatic conditions, and by the amount of leaching.

The optimum concentration of soluble salts in soil solutions of irrigated soils is within the limits of 3–5 g/l. Cultivated plants show slight stress at around 10–12 g/l, and they die at concentrations of 20–25 g/l (Kovda, 1961). Therefore, irrigation with water having a relatively high salt content (2–5 g/l) will still serve to dilute the soil solutions. If the dilution is sufficient and the excess salts are leached out, no damage to the crops will result. It is only when salts are allowed to accumulate, because of insufficient leaching and/or inadequate drainage, that permanent damage results. Therefore, the allowable salt content of irrigation water depends on the amounts of water applied and subsequently removed (Kovda et al., 1967).

Improving water quality

Frequently, the only alternatives open to the farmer whose water is of extremely poor quality are: not to irrigate at all or to use water for supplemental irrigation only.

TABLE 13.1
Guidelines for interpretation of water quality for irrigation

Irrigation problem	Degree of problem		
	No problem	Increasing problem	Severe problem
Salinity (affects water availability to crop)			
ECw (mmho/cm)	<0.75	0.75–3.0	> 3.00
Permeability (affects infiltration rate of water into soil)			
ECw (mmho/cm)	>0.5	0.5–0.2	< 0.2
adj. SAR	<6	6–9	> 9
Specific ion toxicity (affects only sensitive crops)			
sodium (adj. SAR)	<3	3–9	> 9
chloride (meq/l)	<4	4–10	>10
boron (mg/l)	<0.5	0.5	2.0–10.0
Miscellaneous effects (affects only susceptible crops)			
NO ₃ N (or) NH ₄ N (mg/l)	<5	5–30	>30
HCO ₃ meq/l (overhead sprinkling)	<1.5	1.5–8.5	> 8.5
pH	(Normal range 6.5– 9.4)		

< means less than.
 > means more than.
 ECw means electrical conductivity, a measure of water salinity.
 adj. SAR means adjusted sodium adsorption ratio.
 NO₃ N means nitrogen in the water in form of nitrate.
 NH₄ N means nitrogen in the water in form of ammonia.
 pH is a measure of activity (0–7) or of alkalinity (7–14); pH = 7 is neutral.
 From Ayers and Branson (1977). By permission of California Agriculture (University of California).

There are, however, cases in which it is possible to improve somewhat the quality of water with a relatively high sodium and low calcium content, by increasing the proportion of Ca^{2+} ions in the irrigation water. Gypsum is an inexpensive source of relatively soluble calcium, which reduces the sodium : calcium ratio in the irrigation water. Added gypsum also increases the infiltration capacity of soils that have already been adversely affected by irrigating with sodic waters.

Management practices

The methods of irrigation practised, the efficacy of drainage, the maintenance of a favourable soil structure and of a high level of soil organic matter, and other agromomic practices affecting soil fertility, all have a bearing on the quality of water that can be used safely for irrigation.

Guidelines for the interpretation of water quality for agriculture that could be used in comprehensive water management plans were prepared by the University of California Committee of Consultants, in collaboration with the US Salinity Laboratory and staff of the California water Resources Board. These guidelines are summarized in Table 13.1.

Effect of irrigation water on soils

Irrigation water affects the soil by changing both the concentration of the soil solution and the composition of the constituents in solution as well as those adsorbed by the exchange complex (Bower, 1961).

Salt balance

The amount of soluble salts added to the root zone will depend on the amount and quality of the water that passes through this zone during a period of time (Fig. 13.5).

The primary components of the salt balance can be calculated from the concentrations and volumes of flow of water into and out of the soil. In addition, salts can be added to the soil solution by applying fertilizers or soil amendments, or the dissolution of soil minerals. Conversely, slightly soluble salts (gypsum, lime) may be precipitated and become part of the solid phase of the soil. Some salt is also removed by the crop. A quantitative knowledge of salt balance is important only insofar as it influences the soil solution, because crop growth is affected by the concentration of the salts in the soil solution (Rawlins, 1981).

Effects of salinity

The magnitude of these effects will depend on the frequency of irrigation, the

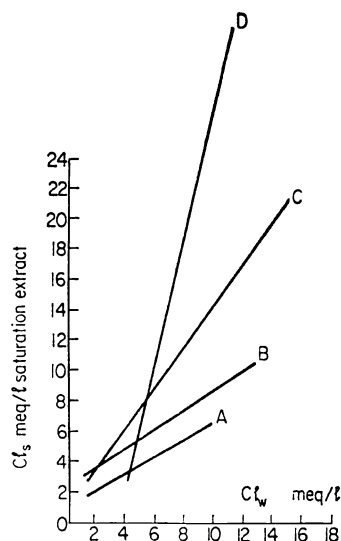


Fig. 13.5. Accumulation of chloride in four different soils (CL_s) as a function of chloride content of irrigation water (Cl_w). A=sandy soil; B=sandy clay-loam; C=clay-pan soil; D=grumosolic dark-brown soil. From Salinity Survey, State of Israel.

amounts of water removed by evapotranspiration, the depth of the groundwater table, the concentration of salts in the groundwater, and the permeability of the soil. Irrigation usually results in a gradual increase of salts in the root zone, causing salinization of the soil. The abundance of soluble salts maintains the soil colloids in a flocculated condition, and therefore has a favourable effect on soil structure and permeability.

As soluble salts accumulate in the soil and the soil solution becomes more concentrated, the solubility limits of calcium sulphate, calcium carbonate, and magnesium carbonate, may be exceeded, causing precipitation of calcium and magnesium. This results in a corresponding increase in the relative proportion of sodium in the soil solution.

There exists an equilibrium between the cations in the soil solution and those adsorbed on the exchange complex. As the relative proportion of sodium in solution increases, more sodium is adsorbed on the exchange complex. This process will in due course cause the soil to become both saline and sodic.

The increase in exchangeable sodium has a marked influence on the physical properties of the soil, the main effect being the tendency to cause the dispersal of the soil colloids. As long as sufficient non-sodic salts are present, even sodium-saturated clays remain flocculated. However, if soluble salts are removed from the soil by leaching, changing the saline sodic into a non-saline sodic soil, the soil colloids are dispersed and the soil structure then deteriorates. Water applied then no longer

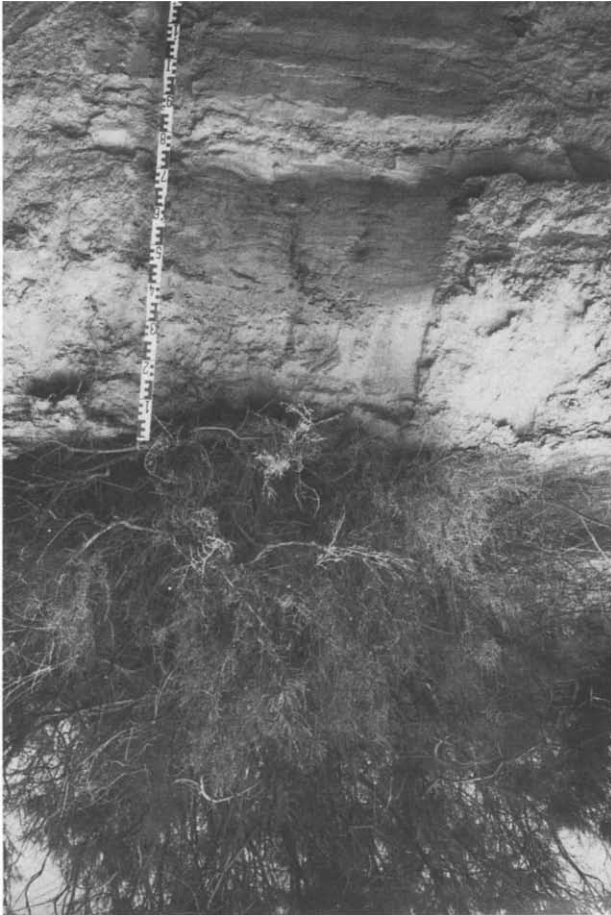


Fig. 13.6. Profile of a Salorthid soil. Photo J. Dan.

percolates easily, the soil does not drain well, and oxygen levels become low (Fig. 13.6).

Plant growth in such sodic soils will become restricted by greater water deficits, greater soil resistance, and reduced hydraulic conductivity. These adverse effects become acute when the exchangeable sodium percentage reaches about 15% (Power, 1990).

Effects of salinity on crops

Salts affect plants directly in two ways: by increasing osmotic pressure and by the

specific toxicity of their ions. Which of these two is the major factor, is still subject to discussion; as the two kinds of effect occur simultaneously, it is very difficult to elucidate their mechanisms. Indirect effects may also result from nutritional disturbances, and from the effects of salts on micro-organisms and on soil structure – the last-mentioned often resulting in adverse physical conditions for plant growth. All these factors naturally affect crop yields in various degrees, depending on the susceptibility of the crop (Fig. 13.7).

Osmotic effects

Up to a certain threshold level that is specific for each crop, salt-affected plants often appear no different than plants suffering from drought, but wilting does not occur as frequently. The osmotic potential of the soil solution generally increases gradually, as soil moisture decreases between irrigations, giving the plant the opportunity to adjust its internal osmotic potential gradually, so as to maintain turgor and delay wilting. Osmotically active organic compounds are synthesized within the cells, and inorganic ions from the surrounding environment absorbed into the cells. Moderate salinity can therefore often remain undetected because it causes no visual injuries, other than slightly restricted growth (Rawlins, 1981).

However, the increase in osmotic pressure of the soil solution due to high concentrations of salts, irrespective of the kinds of salts, increases the amount of energy which the plant must expend to take up water from the soil. As a result, respiration is increased, and growth and yield of most plants decline progressively as the osmotic pressure increases (Grillot, 1956). Beyond the threshold level mentioned above, dehy-

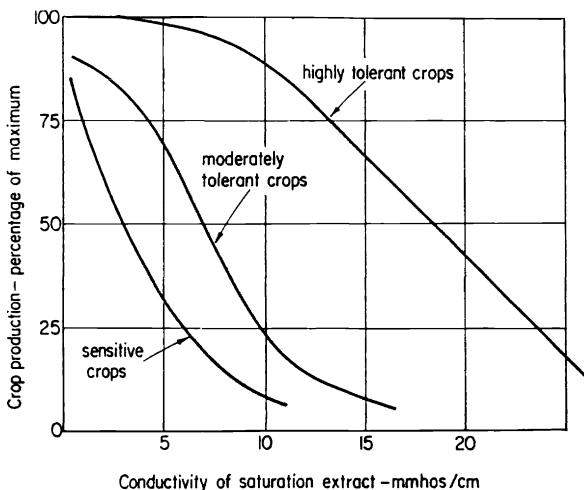


Fig. 13.7. General relationship between crop production and soil salinity. From Fireman and Kraus (1965). By permission of Tahal-Water Planning for Israel.

dration of the biological system becomes severe enough to reduce physiological activity (Steponkus, 1980). Root growth is also suppressed, increasing the difficulty of water uptake. Salinity stress in plants is often called 'physiological drought'.

The growth reduction due to increasing salinity is generally linear within a wide range. Leaves of salt-affected plants are smaller than normal leaves, and are darker green. Salinity may also cause greater succulence, especially if the chloride concentration is high (Rawlins, 1981).

For most crops, relative yields are more depressed at a given osmotic potential in warm climates than in cool climates (Magistad et al., 1943).

In contrast to the gradual increase in the osmotic potential of the soil solution as the soil dries out between irrigations, which allows osmoregulation by the plant, the concentration of salts is suddenly reduced after irrigation. This is followed by a sudden, excessively rapid uptake of water which may occasionally cause the rupture and death of cells (Grillot, 1956).

Because salinity levels are generally not uniform over an irrigated field, a distinctive characteristic of a salt-affected crop is the uneven stand, with bare spots and patches of stunted plants (Rawlins, 1981).

Toxic effects

Many of the ions which are harmless or even useful at relatively low concentrations may become toxic to plants at high concentrations. The ions that are most likely to be toxic to plants are chloride, sodium, bicarbonate, sulphate, and boron (Hayward, 1956).

Visual symptoms of specific solute toxicity, such as marginal or tip burn of leaves, usually occur only in woody plants. In more extreme cases, the leaves dry and fall. Chloride sensitive crops usually show injury symptoms when their leaves accumulate between 0.3 and 1% chloride on a dry-weight basis, depending on the crop. Sprinkling with water containing toxic solutes is particularly damaging. Non-woody plants may often accumulate as much of the toxic ions as woody species without visual symptoms. Leaf symptoms do not always result in yield decreases (Rawlins, 1981).

Anatomy and physiology of salt-affected plants

In addition to retarding all growth processes, including cell division and enlargement, salinity reduces the production of proteins and nucleic acids; it affects the structure and integrity of plant membranes and causes mitochondria, the golgi system, and chloroplasts to swell.

Toxic ions, such as Na^+ , Cl^- , etc., may disrupt basic structures of protein molecules; chloride causes fewer stomata per leaf area and a poorly developed xylem system (Maas and Nieman, 1978).

*Indirect effects**Nutritional effects*

The excess of certain ions frequently has a disturbing effect on the absorption of other ions. For example, high concentrations of sulphate generally decrease the uptake of calcium whilst promoting the uptake of sodium, thereby causing sodium toxicity in susceptible crops. High concentrations of calcium may interfere with the uptake of potassium (Bernstein and Hayward, 1958). Saline soil containing a high proportion of magnesium to calcium, may cause Ca deficiency in plants.

The increased pH, due to the increment of sodium carbonate reduces the availability of P, Fe, Zn, and Mn (Magistad, 1945).

Soil micro-organisms

Barren alkali soils contain a rich microflora, capable of surviving under air-dry conditions for very long periods. The sensitivity of different micro-organisms varies widely: ammonia-producing organisms and *Azotobacter* are relatively resistant, whereas nitrate- and nitrite-producing organisms are far more sensitive. Alkali salts become toxic to nitrifying micro-organisms before they harm many higher plants, and it is possible that, at such lower concentrations, the harm done by salts is indirect, through their effect on nitrification (Greaves and Jones, 1941).

Effects of impaired structure of sodic soils

The impaired soil structure of sodic soils may adversely affect plant growth as a result of poor aeration, nutritional disorders, and poor permeability to water (Magistad, 1945).

Crop tolerance to salinity

The tolerance of crops to salinity depends not only on genetic traits, but also on the stage of growth and environmental factors.

Salt tolerance appears to be related either to an ability to control intake of Na^+ and Cl^- ions, or to a tolerance to a high level of chloride content before leaf injury occurs (Vose, 1963). Susceptible trefoil varieties absorbed more chloride than did resistant varieties (Hayward and Wadleigh, 1949), whilst susceptible cotton varieties contained more sodium than did tolerant varieties (Richards, 1954). Similarly, salt-susceptible varieties of barley had higher Na and chloride and lower K contents than did resistant varieties. The grain yield and 1000 grain weight of the susceptible varieties were reduced at a relatively low level of NaCl, at which the resistant varieties remained unaffected (Greenway, 1962).

Most field crops are, however, not harmed by the absorption of quite high concentrations of sodium or chloride. An excess of bicarbonate may be toxic to sensitive

crops such as dallis grass and field beans (Allison, 1964); boron may be extremely toxic at certain levels, as already mentioned (p. 526).

Factors influencing the tolerance of crops to salinity

Species and cultivars

There are, occasionally, marked differences in the susceptibility to salinity of different species and of cultivars of the same crop. Thus Egyptian long-staple cotton cultivars are less sensitive than the medium-staple American cultivars, while marked differences in salt tolerance can exist between closely related cultivars of soybeans.

Most widely known varietal differences in salt tolerance are between grass species, and to a lesser extent between forage legumes (Rawlins, 1981).

Tolerance to salinity is genetically controlled, but inheritance is relatively complex, and – like yielding ability – it varies with climate and other environmental conditions (Peterson, 1961).

Although it has been shown that genetic variation can be used to develop cultivars suitable for growing on salt-affected soils, “progress in this enterprise has so far been modest” and “the number of breeders addressing the problems of salt tolerance is as yet miniscule” (Epstein and Rains, 1987).

Age of plant

Plants are frequently found to be salt-tolerant either in the germination and seedling stage, or at a later stage of growth, or in both. Therefore the degree of tolerance of a crop to salinity must be evaluated at three stages of its growth, namely those of germination and seedling establishment, vegetative growth, reproduction and maturation.

Germination failures due to salinity occur frequently; often this is not because the crop is particularly sensitive to salinity during germination, but because of high concentrations of salts in the shallow soil layer in which the seed is placed (Bernstein, 1962). These salt concentrations are due to salt residues as upward moving water evaporates from the soil surface (Rawlins, 1981).

At relatively low concentrations, increasing salinity causes a progressive retardation of germination; at higher concentrations the *ability* to germinate is reduced. Certain ions may also have a toxic effect that reduces germination or causes abnormalities in the embryo or seedling.

The higher the temperature is above optimum levels, the more will the sensitivity to salinity increase (Hayward and Wadleigh, 1949). The effects of salinity on germination increase as soil moisture-tension increases, and vice versa.

There is, however, not always a correlation between the relative resistance of crops to salinity at germination and that at later stages of growth. Thus most crops are more sensitive to salinity in the seedling stage than at later stages: sugar beets, for example, are very sensitive to salts in the seedling stage, being affected by a conduc-

tivity of 4–5 mmho/cm, but they become one of the more resistant crops as they develop, tolerating up to 12–15 mmho/cm in their later stages of growth (Reeve and Fireman, 1967). There are, however, exceptions:

Maize, which is less tolerant during later stages of growth than in early ones, gives satisfactory germination at salinity levels which adversely affect the germination of sugar beet and lucerne seeds (Hayward and Wadleigh, 1949). Rice germination is normal at salinities up to 10–15 mmho/cm, but the seedlings usually die at salinities in excess of 5–6 mmho/cm; at a later stage of growth, the plants are less sensitive to salinity (Pearson and Ayers, 1958). For this reason, it may be necessary to drain the paddy field during a sensitive stage, refilling it with fresh water in order to lower salinity (Allison, 1964).

Vegetative growth

As already pointed out, vegetative growth is depressed as the osmotic pressure of the soil solution increases. At first, the rate of growth may be reduced without any external signs of injury, and it is not always easy to recognize salt injury in the field. However, with increasing salinity, visible modifications in leaf structure may appear: the cuticle becomes thicker, with a tendency towards succulence in some crops; the leaves develop a waxy bloom and a deep blue–green colour. At high salt levels, certain crops, such as barley, sorghum, and field beans, may show leaf-burn (Eaton, 1942).

On passing from the vegetative to the reproductive stage, there is generally a marked increase in salt tolerance (Pantanelli, 1937).

High osmotic pressure of the soil solution usually causes reduced yields, but not in all cases are vegetative growth and yielding ability affected equally. For example, the vegetative growth of barley and cotton is more affected by salinity than are the yields of the economic product, grain and fibre, respectively, so that relatively stunted plants can still give fair yields (Reeve and Fireman, 1967).

Among the more salt-tolerant forage crops, yields of seed are less affected by salinity than are forage yields (Ayers et al., 1952). By contrast, rice may produce normal straw yields at a level of salinity that adversely affects grain production (Kapp, 1947).

Soil fertility

Crops grown on infertile soils may seem to be highly tolerant of salinity compared with those grown on fertile soils; this is because soil fertility, in this case, is the limiting factor and not salinity. Adequate fertilization increases the yields of the crops grown under saline and non-saline conditions, but not proportionally. Fertilizers applied in excess of requirements can significantly raise soil salinity (Rawlins, 1981). In a study by Heakal et al. (1990), an ample supply of potassium produced substantial improvements in salinity tolerance in the two crops tested: wheat and

barley; increasing K supply reduced the rate whereby yields decreased as a result of salinity.

Climate

Temperature and air humidity can influence crop tolerance to salinity. High relative humidity tends to reduce sensitivity of crops to salinity; hot weather has the opposite effect (Rawlins, 1981). However, not all crops behave alike in their reaction to the combined effect of salinity and climate. The yields of some crops are reduced equally by a given concentration of salts in the soil, irrespective of climate (Magistad et al., 1943).

Models for assessing water suitability for irrigation

Ideally, the assessment of suitability of water for irrigation should take into account the specific conditions of use, including the crop grown, soil properties, irrigation management, cultural practices, and climatic factors (Rhoades et al., 1989).

A computer model has been developed that relates to these requirements by: (a) predicting the composition, osmotic potential, and matrix potential of the soil water in the root zone both in time and space, resulting under specific conditions of management and climate; (b) interpreting such information in terms of how suitable are the resulting soil conditions for rooting and how the crop in question would respond to such soil and climatic conditions (Rhoades, 1984).

Management practices for maintaining the productivity of irrigated soils

The salt balance in the soil depends on maintaining a proper water balance. Therefore, the effective control of salinity depends on all management practices that are related to the amount of water used, the frequency with which it is applied, and its movement in the soil. Among these practices are:

- (1) the preparation of the land to be irrigated, and soil management;
- (2) the methods of irrigation adopted;
- (3) the amounts of water applied and the frequency of irrigation, according to crop needs;
- (4) the maintenance of a 'salt balance' by leaching; and
- (5) the removal of excess water and salts by drainage.

Levelling

A careful levelling of the areas to be irrigated as well as careful planning of the irrigation layout, are essential in order to ensure a uniform distribution of water in surface methods of irrigation. With overhead irrigation, this is less critical. When irrigation water is not uniformly distributed throughout the irrigated area or water

infiltration is not uniform, leaching is not uniformly effective: there are then tendencies for excess leaching to occur in the low areas and for salts to accumulate in the high ones.

Soil management

All soil management practices that improve the infiltration rate and maintain a favourable soil structure will contribute to salinity control.

Mulching has been found helpful in keeping down salinity in localized saline soil areas by reducing evaporation from the soil surface, so that less salt accumulates, and by improving percolation rates, so that excess salts are more easily removed by leaching.

On a saline-sodic soil with a high salt concentration, it was found that a cotton-bur mulch facilitated leaching of soluble salts by rainfall. Salt concentration was thus reduced to a safe level for field crops in the surface 75 cm of soil (Fanning and Carter, 1963).

Methods of sowing

Following irrigation, there are sometimes considerable differences in the concentration of salts in the soil, depending on micro-relief. Even in soils that are non-saline, enough salt may accumulate in seedbeds on flat-crowned ridges to prevent germination (Bernstein and Ayers, 1955). With furrow irrigation, for example, the salts will tend to concentrate mainly in the centre of the ridge between furrows and in a thin layer along the top of the ridge, decreasing on the slopes of the furrow, to reach a minimum at the bottom of the furrow (Bernstein, 1962). Therefore, the most dangerous location for the seedrow is in the centre of the ridge, and the safest is at the bottom of the furrow. At this location the emerging seedling may, however, suffer from crusting of the soil surface. Methods proposed for minimizing salt accumulation in the vicinity of the seeds include: additional irrigation under low evaporative conditions (e.g. at night), modifications in planting practice (such as maintaining furrows between flat-topped ridges as full of water as is practicable), using low ridges, planting in V-depressions on otherwise flat ridges, cf. Fig. 13.8 (Lyerly and Longenecker, 1964).

From research carried out by Bernstein and Ayers (1955) the most successful seedbed would appear to be on a sloping ridge, with the seed planted on the slope of the ridge, several inches below the crown of the ridge.

The salt is carried beyond the line of sowing and therefore leaves a non-saline zone for the germinating seed. Germination under these conditions has been found to be satisfactory, even when salinity in the ploughed layer as a whole was as high as 30 to 40 mmho/cm at the time of ridging.

Crop rotation

Crop rotation can be very effective in controlling salinity. The inclusion in the rota-

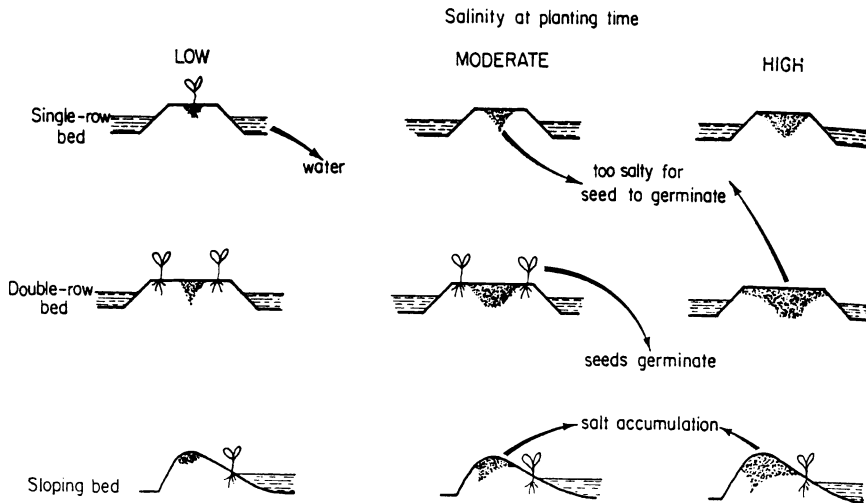


Fig. 13.8. Effect of soil salinity and bed type on salt accumulation in a seeded area. Germination is prevented or delayed where salt accumulation is excessive. The stippling indicates the positions of salt accumulation. From Lyerly and Longenecker (1964). By permission of World Farming.

tion of such crops as rice, that require higher-than-usual amounts of water, makes possible the leaching of excess salts without damage to the current crop. The inclusion of salt-tolerant crops in the rotation, during periods of leaching and reclamation, is also desirable.

Irrigation methods

Irrigation methods have considerable influence on salinity levels, and in particular on the spatial distribution of the salts in the root zone. Salts will be most uniformly distributed under overhead irrigation. Whilst the uniformity of application of water that is possible with sprinkler irrigation is a great advantage in the prevention of saline conditions, the general tendency is to apply less water than with surface irrigation. This may result in increased salt concentrations in sprinkler-irrigated soils as compared with surface-irrigated fields. Consequently, it is essential to apply sufficient water periodically for leaching, when overhead irrigation is used (Hobbs and Russell, 1967).

Furrow irrigation causes the maximum concentration of salts to occur in the location in which damage to plants is greatest (see Fig. 13.9). Localized accumulation of salts is also typical for raised beds, ridges, or borders. Under conditions that are conducive to high salinity, the border method of flooding is more suitable than furrow irrigation, whilst corrugations are definitely unsuitable. The frequency of irrigation may also affect the degree of salt damage experienced by the crops. It is the

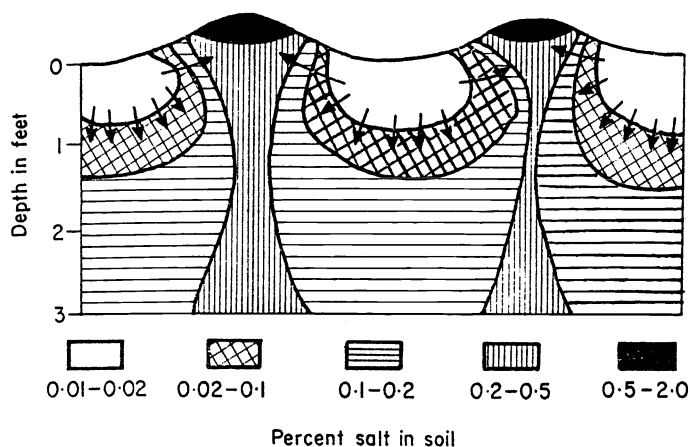


Fig. 13.9. Effect of furrow irrigation on salt distribution in the soil profile. The arrows show the direction of the flow of water and salt during, and some time after irrigation. Salt leaches out of the soil under the furrows and builds up in the ridges. From Lyerly and Longenecker (1964). By permission of World Farming.

concentration of the soil solution that normally causes injury to the crops and not the irrigation water itself. By irrigating at relatively short intervals, it is possible to prevent the soil solution from becoming excessively concentrated. The more saline the growing conditions, the more frequently the crops must be irrigated in order to reduce adverse effects on plant growth. Such more frequent irrigations are, however, associated with greater proportional losses of water by evaporation, and with reduced leaching effects – so that, in the long run, they are conducive to greater increments of salt.

Salt balance and leaching

In order to prevent salinization, a balance must be maintained between the quantity of dissolved salts introduced into the root zone, and that removed from the root zone.

As the irrigation water is the main source of added salts, it would appear at first sight that reducing the amounts of water applied to the bare minimum requirement, is the first essential step in reducing salinity hazards. However, experience has amply proven that only by using water in excess of consumptive use, can salt accumulation in the root zone be prevented unless, of course rainfall is adequate to do the leaching during the rainy season.

The irrigation farmer therefore faces two contradictory requirements: on the one hand he is required to apply water not in excess of crop requirements in order to avoid waste and also a rise in the water table with all its attendant ills; on the other hand, soil salinity will increase unless he applies water in excess of what is actually

needed by the crop. Small wonder that primitive agriculture systems were not able to solve this dilemma!

Leaching requirement. The quantity of salts that accumulates in the root zone during an irrigation season depends on the amount of irrigation water applied, and on its salt content. The amount of additional water which must pass through the root zone in order to reduce soil salinity to a predetermined level, called the 'leaching requirement', is also dependent on the same two factors.

Bernstein (1962) has established a formula that gives an estimate of the leaching requirement (LR), based on maintaining a balance between the amount of salts that enter the root zone and the amount that is removed. The equation gives an approximation only, as it does not take into account the precipitation of certain salts, their uptake by plants, fertilizer applications, etc.

The amount of salt that enters the root zone with irrigation is:

$$EC_{iw} \times D_{iw} \times K, \quad (1)$$

and that leaving the root zone is:

$$EC_{dw} \times D_{dw} \times K, \quad (2)$$

where EC is the electrical conductivity, D is the depth of water applied or drained per unit area, K is a constant, iw refers to irrigation water, and dw refers to drainage water.

In order to prevent accumulation of salts in the root zone, the amount of salts removed must be at least equal to the amount added, so that:

$$EC_{iw} \times D_{iw} \times K = EC_{dw} \times D_{dw} \times K,$$

from which is derived the equation:

$$LR = \frac{D_{dw}}{D_{iw}} = \frac{EC_{iw}}{EC_{dw}}. \quad (3)$$

EC_{iw} is known from the analysis of the irrigation water and EC_{dw} is established according to the maximum permissible salt concentration of the crop involved.

The EC_{dw} is related to the salt tolerance of the crop. Originally, the criterion used for EC_{dw} of soil samples taken from the bottom of the root zone (EC_e) was that EC_e values that produced 50% yield decreases in field and forage crops should be used as estimates of EC_{dw} . Subsequently, Bernstein and François (1973) concluded that crops are relatively insensitive to high salinities in the lower root zone, and that LR can be reduced for crops that are tolerant or moderately tolerant to salinity. They recommended that EC_e values obtained from salt-tolerance tables be increased about two-fold before substitution for EC_{dw} in the LR equation.

Information on consumptive use of water by the crop (ET) is necessary if LR is to

be used for determining the depth of irrigation water to be applied (D_{iw}) or depth of water to be drained (D_{dw}) in order to maintain a given salinity level in the soil (James et al., 1982).

The relationship between ET and D_{iw} and D_{dw} is:

$$ET = D_{iw} - D_{dw}$$

The leaching requirement may vary from 15% above the water requirement, when high-quality irrigation water is used, up to 70% above the water requirement, when relatively saline water is used and the crops grown are particularly susceptible to salts (Fig. 13.10). It is frequently possible to apply a heavy (leaching) irrigation at the beginning of the season, to be followed by irrigations at the normal rates (based on evapotranspiration and irrigation efficiency) throughout the growing period of the crop. Amounts of rainfall of less than 250 mm annually are insufficient to affect the leaching requirement appreciably (Eaton, 1954), whilst with 450 mm annually, irrigation leaching may become unnecessary (Kelley, 1951). The effectiveness of rainfall in leaching is considerably increased if the root zone is left wet to field capacity at the

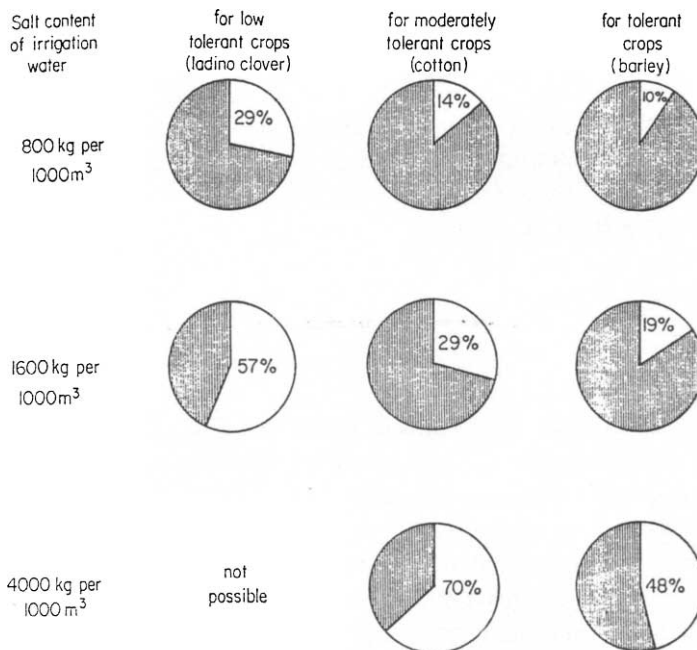


Fig. 13.10. Leaching requirements in relation to water quality and the salt tolerance of crops. The leaching requirement expressed as percentage of the irrigation water (white area) that must pass below the root zone to prevent an appreciable reduction in crop yields. From Lyerly and Longenecker (1964). By permission of World Farming.

end of the irrigation season and the onset of the rains. Effective leaching is of course possible only if the water table is very low or where drainage is satisfactory.

Leaching methods. Basically, there are three methods used for leaching:

- (1) Continuous ponding (leaching prior to growing the crop).
- (2) Ponding with a rice crop (continuous leaching).
- (3) Applying water in excess of irrigation requirements during the growing of a crop (intermittent leaching).

Fertilization

Fertilization is not effective in a very saline soil, but is doubly important after salinity has been reduced by leaching, as this also removes much of the plant nutrients, and in particular nitrates, from the root zone.

Excessive fertilization may contribute to salinization. Certain fertilizer salts are more dangerous in this respect than others: the application of sodium nitrate, for 27 years, increased the exchangeable sodium content of a soil at Riverside, California, from an initial value of 2% up to 20–30% (Bernstein, 1962).

Drainage

As a general rule, irrigation results in a significant rise in the level of the groundwater, which, in arid regions, is usually much more saline than in humid regions (Kelley, 1951). Water in excess of consumptive use has to be applied in order to flush away the salts that have accumulated in the root zone. In addition, the general tendency is to apply water in excess of crop requirements. Seepage from irrigation channels and other losses of water through faulty management, as well as precipitation during the rainy season, also contribute to a rise of the water table. When the water table has reached the root zone, capillary rise of the salt-laden water and the removal of water by evapotranspiration, leave behind a greatly increased concentration of salts in the root zone.

There are many cases in which the water table rises to within one metre of the soil surface, creating conditions under which crop plants can no longer be grown profitably and leaching of excess salts is of course no longer possible. Indeed the introduction of irrigation in arid regions will generally result in drainage problems, unless adequate natural drainage exists.

Conditions under which satisfactory natural drainage can occur at all widely in arid regions are not common.

Natural drainage by deep percolation occurs when there is a very porous substratum, with a considerable groundwater gradient (Jewitt, 1966) and the drainage waters eventually reach waterways or depressions.

In the rare situations in which good natural drainage exists, history has shown that irrigation can be practised for thousands of years without salinization. This was the

case for Egypt, in the areas bordering on the course of the Nile, which have natural drainage towards the river after it has subsided. This drainage was adequate as long as basin irrigation was practised, but was no longer effective after the traditional once-yearly flooding and basin irrigation were replaced by perennial irrigation, which has practically eliminated the low-water stage; subsequently, salinization problems became acute and artificial drainage became a necessity.

Drainage has the dual function of removing excess salts and excess water. *Surface drainage* is necessary to remove excess surface water that is due to irrigation and rainfall, preventing its percolation to groundwater and the formation of a water table near or in the root zone. *Subsurface drainage* is necessary to control the height of the water table and to remove excess salts. This can be achieved only if the hydraulic conductivity is sufficient and if there are adequate outlets for the drained groundwater.

If the natural subsurface drainage is not sufficient to carry away excess water from a field, an artificial subsurface drainage system becomes necessary. The system may consist of open ditches, buried drainage pipes, or pumped drainage wells. The exact depth at which the water table should be maintained for optimal plant growth and salinity control is not a fixed value; experience has shown that a depth of approximately 2 m will ensure that salt accumulation will not be a problem with normal irrigation practice (James et al., 1982).

Well irrigation, where practiced, contributes to maintaining a low water level.

Generally, there is a tendency to overvalue natural drainage, and undervalue seepage during distribution and following water application. However, artificial drainage is costly, and its need is not immediately apparent. Therefore, administrators of irrigation projects generally give priority to expanding the irrigated area to the full extent allowed by their budget, rather than restrict the initial area, in order to develop concurrently an effective drainage system (Worthington, 1977).

Because it is difficult to predict accurately the precise sites at which the water table will eventually need to be lowered, Rawlins (1981) suggests that irrigation should begin simultaneously with a programme to monitor groundwater table elevations to locate the problem sites that will require drainage. This procedure makes it possible: (a) to plan ahead of the time when drainage will become inevitable; (b) provides the information for planning an effective drainage system; and (c) makes possible phased implementation.

Magnitude of the problem. In regions in which the main source of water supply is from pumped wells, there is generally little danger of raising the water table, and drainage problems are usually minor. Well irrigation may even improve the situation in locations where the soil is waterlogged to begin with. In the San Joaquin Valley of California, for example, wells which supply irrigation water also serve successfully for water table control (Donnan and Hudston, 1967). The water that is extracted from the aquifer is replaced by percolation from the waterlogged root zone.

The problem generally becomes acute where water is 'imported' into the irrigation area and it is in these irrigation systems that waterlogging is inevitable, wherever drainage is inadequate. Sometimes, the water table rises rapidly, but generally the rise is a few centimeters annually. The rise of the water table is associated with secondary soil salinization. The process is due to salinity of the groundwater or is caused by diluted soda-carrying irrigation waters (e.g. the Nile, the Indus). In extreme cases, the cation exchange complex of the soil becomes saturated with sodium up to 50–70%, and the pH rises to 9–11. Soil degradation by compaction always follows (Kovda, 1977).

In general, project managers and farmers delay attacking the problem of drainage until the situation has deteriorated to the extent that economic crop production is no longer possible without reclamation. The carrying out of drainage works as a preventive measure is unfortunately still the exception. Yet, in many cases, artificial drainage would be unnecessary if conveyance losses to the field were eliminated and excessive quantities of water application to the crop were avoided.

Drainage is generally a regional problem, because even the most careful farmer may be penalized by waterlogging of his fields resulting from seepage from near-by irrigation canals over which he has no control. Frequently, excess water from high-level lands seeps through lateral aquifers, to reappear in lower-lying lands – sometimes many kilometres downstream (Luthin, 1957). In many cases, bringing upstream areas under irrigation has caused the loss of better areas downstream, as a result of the rise of water tables in the latter.

For drainage to be effective, it is necessary to lower the water table over a fairly large area. This cannot be achieved by the individual farmer, but requires a community effort (Kelley, 1951). In general, the costs of major drainage schemes are borne by governments which also administer the drainage projects of districts. The costs of drainage of individual land tracts are generally borne by the owners – although government subsidies and loans on easy terms are available for this purpose to landowners in most countries in which drainage problems are acute.

Desirable depth of the water table. The depth to the water table is important in determining the rate of downward water movement practical under irrigation (Rawlins, 1981).

Under natural conditions, upward movement of water from high water tables has led to extensive areas of saline soils, and a number of authors have tried to define a '*critical water depth*' below which soil salinization will not occur. Rawlins (1981) points out that "although the rate of water transport to the soil surface decreases as the depth to the water table increases, it never reaches zero. As a consequence, given sufficient time, any net upward flow from a water table, no matter how deep, will result in soil salinization". The author concludes that prevention of salinization does not depend only on the depth of the water table but on the maintenance of a long-term balance between upward and downward flow to the soil surface.

Irrigating with brackish water

Considerable quantities of saline water, that are considered unfit for irrigation by conventional standards, are available in many places in the world. Shallow groundwaters and drainage waters in the US, the former USSR, Pakistan, Egypt, and Australia belong to this category (Rhoades, 1984). Irrigated areas could be considerably expanded if less rigorous standards than those conventionally accepted for evaluating water quality and fitness of soils for irrigation, were applied under suitable circumstances.

Experience and recent studies have shown "that water previously thought unsuitable for irrigation can often be used successfully to grow crops without hazardous long-term consequences to crops or soils" (Rhoades et al., 1989).

In the US, extensive areas of lucerne, sorghum, and wheat are irrigated in the Arkansas Valley with water containing 1.5 to 5 g/l TDS (Miles, 1977). In the Pecos Valley, water averaging 2.5 g/l has been used for decades (Moore and Hefner, 1976).

Highly saline waters, with salt concentrations of 3 to 8 g/l are frequently used for irrigation during very long periods in Central Asia, the Near East, and North Africa. This is possible when salt-tolerant crops are grown, the soils are very sandy, the water is high in gypsum content, and is applied at high rates and under conditions of excellent natural drainage.

In southern Tunisia, water with over 5 g/l of total salts, of which 1.2 g/l is sodium, has been used under these conditions for long periods. Yields are low because of lack of fertilizers, inadequate pest control, etc., so that salts are not a limiting factor under these circumstances (Kovda et al., 1967a,b). Elsewhere in Tunisia, irrigation with water that had a total salt content of 2.68 g/l did not appreciably increase soil salinity after three years, though some increase in salt concentration in the root zone was noted. During this period the yields of maize were reduced by 6 to 10% (not significant), and those of lucerne by 11 to 12%; by contrast, the yields of wheat were increased by 35%, approximately, and those of cotton by 15 to 20% (Cointepas, 1964). In Israel, water containing 2.3 g/l of total salt, of which 1 g/l is chloride, has been used on sandy soils without apparent damage (Shalhevet and Reiniger, 1964).

Keren and Shainberg (1978) report that cotton is grown commercially in Israel with water containing 2.8 g/l TDS.

In certain regions of Italy, in particular in the province of Bari, irrigation with high salt water has been practised for a long time (Bottini, 1961). The waters used contain up to 8–10 g/l of salts. The soils are sandy to a depth of several metres, and are therefore very permeable, with excellent natural drainage; they are also rich in calcium and organic matter. During the growth period the soil is maintained at a high level of moisture by frequent irrigations. Irrigation is practised in one summer out of two, whilst the salts are leached out by two successive seasons of winter rainfall amounting to 400–600 mm each. Even with these precautions, not all crops can be

grown: maize – a moderately tolerant crop – gives very low yields under these conditions. The crop that is generally grown is tomatoes.

In a worldwide survey of irrigation and salinity, Shalhevet and Kamburov (1976) found that waters of up to 6 g/l TDS were being used successfully.

The few examples presented above are sufficient to indicate that waters of higher values than those acceptable by conventional norms can be used for irrigation under certain circumstances; the latter include the use of tolerant crops, grown on sandy soils with good drainage, and appropriate management practices.

When brackish water is too saline to be applied directly, even to salt-tolerant crops, the customary approach is to blend the brackish water with water of low salinity, so that the concentration of salts in the blend does not exceed the accepted safe limit. This is the system used on a national scale in Israel, where the water in the National Water Carrier, which supplies most of the irrigation water in the country, is actually a regulated blend of water from different sources.

Rhoades et al. (1989) propose an alternative system, whereby the use of brackish water is enhanced in a dual rotation (crop and water) system of management. The system is based on the following procedures: (a) to include salt-tolerant crops in the cropping sequence; (b) to use non-saline water for irrigating salt-sensitive crops; (c) to use brackish water (e.g., drainage water or shallow groundwater) when irrigating the salt-tolerant crops, after seedling establishment (low-salinity water is used for pre-plant and initial irrigations).

The timing and amount of substitution depend on the respective qualities of the water from the two sources, the cropping sequence, the climate, and the irrigation system.

The authors contend that the soil will not become unduly affected from the use of brackish water for part of an irrigation season or seasons as any deleterious effects are alleviated by the subsequent use of non-saline water on sensitive crops. By applying their system, no significant yield decreases were noted; there was no loss in cropping flexibility or change in current farming operations.

Proper pre-plant irrigation(s) that leach the salts out of the seedbed and shallow soil layer, and careful management during germination and seedling establishment further reduce the danger of a reduction in yield of the sensitive crops.

In brief, the cyclic use of brackish and low-salinity waters prevents the soil from becoming excessively saline while allowing, over a long period, the substitution of up to 50% of the low-salinity water available to the farmer (Rhoades et al., 1989).

Irrigating with seawater

Boyko (1968) was the first and most vocal author to claim that it was possible to use seawater, without blending, for irrigation. His trials were carried out on dune sand

with a xerophytic native grass: *Agropyrum junceum* as the trial plant. Seawater (40 g/l salts) as well as several blends were used for watering the plants grown in open-ended asphalt barrels, placed on sand.

Boyko reported that the salts did not accumulate in the sand but were leached out by seasonal rainfall, that the physical properties of the sand were not adversely affected, and that the trial plant survived several seasons of irrigation. As to the practical application of these findings, Boyko asserted (in a verbal discussion with the author) that it was up to the plant breeders to develop crops that could make economical use of the principles that he, Boyko, had established.

Though more than two decades have elapsed since Boyko's findings, no cultivated crops irrigated with seawater are as yet commercially grown.

Reclamation of salt-affected soils

Salt-affected soils must be reclaimed before economic agricultural production becomes possible. Reclamation procedures depend on the type of problem soil in question, namely whether saline, sodic or saline-sodic (James et al., 1982).

Diagnosis of saline and sodic soils

It has been customary in the past to assess soil salinity in terms of the total salt content of the soil. Soils were considered to be slightly saline when the salt content was 0.3%, moderately saline at 0.7%, and strongly saline at 1%. As field crops gener-

TABLE 13.2

Classification of salt-affected soils according to their chemical properties (Richards, 1954) (By courtesy of the USDA)

Type of soil	Specific conductivity of saturation extract at 25°C in mmho/cm		Exchangeable sodium percentage		pH	
	<4	>4	<15	>15	<8.5	>8.5
Normal	x		x		x	
Saline		x	x		x	
Saline-sodic		x		x	x	
Non-saline sodic	x			x		x

ally respond to the osmotic pressure of the soil solution, the determination of the salinity hazard, based on the electrical conductivity of the saturation extract (EC_e) expressed in mmho/cm at 25°C, gives a better appraisal of the salinity hazard in relation to plant growth than does the total salt content of the soil (Richards, 1954) (Table 13.2).

There is a definite relationship between the EC and the OP of the soil solution. For plants that are sensitive to a specific ion, the concentration of this ion has also to be determined.

The salt concentration in the saturation extract is about half the concentration of the soil solution at field capacity, and about one quarter of the concentration at wilting point. This makes it possible to relate the salinity measurements at saturation to field moisture conditions (Allison, 1964), which is not possible when salinity is expressed in terms of percentages of total salts in the soil.

The most reliable index of *sodium status* of salt-affected soils is the sodium adsorption ratio (SAR) (Richards, 1954). This index takes into consideration changes in the concentration and composition of the salts that are present in the soil solution and are in equilibrium with the soil (Allison, 1964).

An important characteristic of salt-affected soils is that the situation can be changed within a relatively short time, provided the necessary conditions are created.

Reclamation of salt-affected and sodic soils involves:

- (a) the removal of excess soluble salts by leaching with adequate amounts of water;
- (b) the displacement of exchangeable sodium by calcium, by adding either soluble calcium or acidifying agents that solubilize lime present in the soil;
- (c) improving the physical condition of the soil; and
- (d) providing adequate drainage.

Reclamation of saline soils

When the soil structure is favourable and drainage is possible, the reclamation of these soils is relatively simple, and can be achieved by leaching with a sufficient quantity of water.

The traditional basin system of leaching consists of ponding water continuously for a period of two to three months, and then allowing the soil to dry (James et al., 1982). Drying the soil improves soil structure and has additional beneficial effects (cf. p. 682).

Various field studies have shown that intermittent ponding is more effective for leaching excess salts than continuous ponding (Miller et al., 1965). The amount of water required will depend on its quality and on the amount of salts that have accumulated in the soil. As a rule of thumb, in order to reduce the salt content of a soil to about 20% of the initial high value, the depth of leaching water required is equal to the depth of soil to be leached (Allison, 1964).

Reclamation of sodic and saline-sodic soils

Reclamation of these soil types is more difficult and expensive than that of saline soils. The saline-sodic soils have a good structure and relatively good infiltration, which are maintained as long as they contain a high percentage of soluble salts; when these are removed by the leaching processes, in the absence of an abundance of calcium, the saline-sodic soil is transformed into a non-saline sodic soil, which is characterized by a low permeability which makes leaching difficult.

In both soil types, calcium salts in suitable form, or substances that promote the solution of CaCO_3 , have to be added prior to leaching or along with the irrigation water, in order to promote removal of exchangeable sodium. In the case of saline-sodic soils, the addition of soluble calcium prevents the soil from becoming non-saline sodic in the first place, and therefore the deterioration of the soil structure is prevented.

In the case of a soil that is already non-saline sodic, the calcium displaces the sodium from the exchange complex, converting the Na clay into a Ca clay, and thereby improving the soil structure.

Two types of soil amendments can be used to achieve this aim: materials such as gypsum (calcium sulphate) which supplies soluble calcium directly and is suitable for all types, or acidifying agents such as sulphuric acid, iron sulphate, or sulphur, for soils that are rich in calcium carbonate.

Sulphuric acid is more effective for reclaiming calcareous sodic soils than gypsum (James et al., 1982). H_2SO_4 dissolves CaCO_3 and solubilizes many other soil minerals, thereby increasing the electrolyte content of the soil water and promoting flocculation.

The sulphur is inert until it is oxidized by soil micro-organisms to sulphuric acid, which may take time. The acid reacts with the CaCO_3 to form a suitable calcium salt (CaSO_4). The solubility of limestone is too low to permit it to be an effective amendment.

The quantities of amendments required also depend on the quality of the irrigation water used and the amount of exchangeable sodium in the soil to be reclaimed. A usual yardstick is to apply sufficient amendment to replace the adsorbed sodium in the top 15 to 30 cm of soil (Reeve et al., 1955). Soluble amendments can be applied along with the irrigation water.

Sodic soils may be extremely impermeable to rainwater, and yet be relatively permeable to saline water. Such soils can therefore be reclaimed in a relatively short time by first saturating the soil with high-salt water, which serves as a flocculent and as a source of divalent cations. This method is applicable only when the SAR of the leaching water is appreciably lower than the SAR of the saturation extract of the soil to be reclaimed – otherwise more sodium will be adsorbed, rather than released from the soil exchange complex. The saline leaching water transforms the sodic soil into a

saline-sodic soil, thereby flocculating the soil and improving its permeability. After the initial leaching with high-salt water, there follow leachings with successively lower dilutions of the high-salt water with good irrigation water (Reeve and Bower, 1960). The progressive dilution reduces the SAR of the leaching water, thereby improving the sodium ratio in the soil.

Water harvesting for reclaiming alkali soils

In the Indo-Gangetic Plain, there are vast stretches of alkali soils that have remained barren for centuries. As capital resources and irrigation water are not available for reclaiming these soils by conventional means, the Central Soil Salinity Research Institute (CSSRI) in Haryana has developed an ingenious system based on the use of abundant run-off during the monsoon season (Kamra et al., 1989).

By using appropriate water harvesting techniques (cf. p. 125) and with ratios of donor area to receiving area of 2–4 : 1, sufficient run-off water was supplied to the cropped area to reduce the pH in the soil, and enable good growth of a salinity-tolerant forage grass (*Diplachne fusca*).

Yields of forage were satisfactory, and improved from year to year.

Soil management practices after reclamation

Fertilizing and manuring

Leaching not only removes undesirable salts, but also plant nutrients – particularly nitrates, whence the need for relatively high applications of nitrogen fertilizers. After leaching, it is desirable to apply large quantities of organic manure and/or to grow a green-manure crop. Such crops aid in rapidly improving soil structure and raising the level of soil fertility – without requiring the application of considerable amounts of fertilizers, which increase osmotic pressure.

Tillage

Deep ploughing (70 cm and deeper) may be helpful as a first step in reclamation by improving tilth, breaking hardpans, occasionally turning up soil layers rich in gypsum, and overall improvement of percolation.

Crop rotation

A transitional crop rotation, using salt-tolerant or salt-resistant plants, can be used during and after reclamation. Sunflowers, sugar beets, barley, sweet sorghum, lu-

cerne, sweet clover (*Melilotus alba*), and several perennial grasses such as rhodes grass (*Chloris gayana*), can serve for this purpose. The salt-tolerant crops are very effective in accelerating the reclamation process, by improving infiltration and by the effect of the CO_2 given off by their roots, which reacts with the CaCO_3 of the soil to form the more soluble calcium bicarbonate (Kelley, 1951).

Rice is an excellent crop for growing during the period of reclaiming saline soils, as it can support the abundant irrigation required for leaching the salts. However, salinity must be reduced to at most 0.5% before the rice can be grown (Hamdan, 1961). After rice, clover and then cotton or sugar beets can follow.

Under exceptional circumstances, wild plants that are highly salt-resistant and at the same time remove large amounts of salts, such as *Atriplex* and *Kochia* spp., have been recommended (Simonneau et al., 1967).

Drainage

After reclamation, an adequate system of drainage must be permanently maintained, otherwise a new cycle of salinization and alkalization will be started, and the whole process of reclamation will have to be repeated. With proper management practices and adequate drainage, the results of reclamation can be permanent (Kelley, 1951).

Summary

- The *quality* of the water available for irrigation will determine the choice of crops to be grown, the soils that can be used, and the management and irrigation techniques that should be adopted.

- Criteria for assessing the quality of irrigation water are based on the hazards to be expected following their use: *salinity hazard*, dependent on the total soluble salt-content (TSS); *sodium hazard*, based on the sodium adsorption ratio (SAR); *bicarbonate hazard*, based on residual sodium carbonate (RSC); and *toxicity hazard*, usually confined to excessive boron. These criteria cannot be applied rigidly, but must be adapted to regional conditions.

- Irrigation usually causes the salinization of soils, and may frequently culminate, in the long run, in alkalization (accumulation of exchangeable sodium), which causes the soil to become both saline and sodic.

- The salinization and alkalization of the soil can be prevented by careful management and irrigation practices and by maintaining the salt balance of the soil. Whenever necessary, water must be applied in excess of irrigation requirements, in order to leach excess salts beyond the root zone.

- The *leaching requirement* depends on several factors; the most important are the salt tolerance of the crop and the salinity of the irrigation water.

– The tolerance of crops to salinity depends not only on genetic traits, but also on stage of growth and environmental factors.

Irrigation also frequently results in a significant rise in the water table, which may create waterlogged conditions under which crops can no longer be grown profitably.

The twin requirements of removal of excess salts and of excess water frequently make *drainage* an essential complement to irrigation. Drainage is usually a regional problem to be solved by communal or governmental action.

Salt-affected soils can be reclaimed by leaching in the presence of an abundance of soluble calcium and by providing adequate drainage.

By preventing the accumulation of salts and waterlogging, and by maintaining a satisfactory level of fertility (see Ch. 10), the permanence of productivity of irrigated lands can be assured.

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CHAPTER 14

Tillage

Evolution of tillage methods

Traditional methods

The earliest form of tillage was probably practised at the close of the Neolithic period. Small plots of ground were cleared, often with the aid of fire, and then dug with a 'digging stick' – the probable ancestor of the plough (Bishop, 1938). The digging stick in the course of time developed into the footplough, which was provided with a rest on which the cultivator pressed with his foot. At a later stage, one or more individuals would pull the tool with cords, whilst another would hold and push it. When animals replaced manpower, the traction plough was evolved. The first proof of its use is found in a Sumerian seal of about 3500 BC. The plough depicted on the seal is strikingly similar to the wooden plough used to this day by the fellaheen in the Near East. In the Egyptian pyramids, 4000-year-old tablets depicting wooden ploughs drawn by cows have been found (Fig. 14.1).

At a somewhat later stage, an upright tube, open at both ends, was attached to the plough. An attendant would drop the seed through a funnel placed on the tube – the earliest example of the 'once-over' principle of sowing and tilling simultaneously. This method is still in use in the Near East.

Greek and Roman farmers were convinced that loosening and mixing the soil improved its fertility. The Middle Ages was a period of stagnation in agriculture. In the 18th century, Tull (1731) proposed the theory that plants feed on soil particles, and the more the soil is cultivated, the more particles can be absorbed by the plant roots. The 19th century added its spate of theories concerning the role of soil tillage. A few superstitions still prevailed; in 1891 Walden still stated categorically that the use of tillage implements was more effective in feeding plants than was the addition of fertilizers to the soil.

The wooden plough, developed in the Near East several thousand years ago, cannot penetrate the dry, hard soil that develops there during the summer months. The farmer must therefore wait until the rains have moistened and softened the soil,

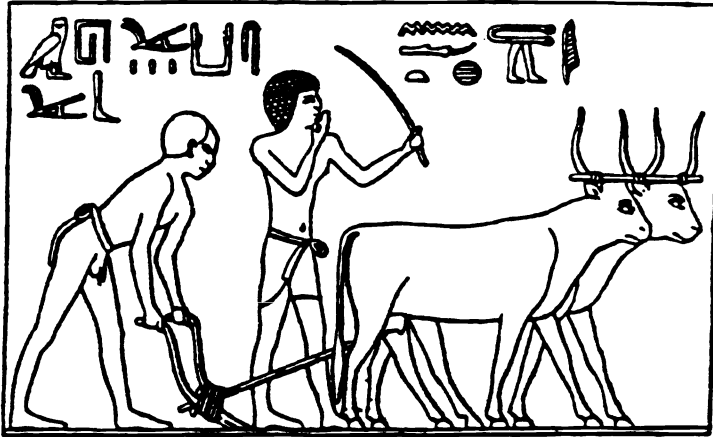


Fig. 14.1. Ancient Egyptian wooden 'stick' plough with two handlebars. Note resemblance to plough in Fig. 8.2a. From Stein (1991). By permission of Sifriat Poalim Publishers.

before he can begin to cultivate. The wooden plough loosens the moist soil, without inversion. Weeds and stubble remain on the soil surface.

Seeds of *winter cereals* and other rain-fed crops are sown broadcast, before ploughing. No other tillage operations are carried out. For summer crops the soil is re-ploughed two or more times during the winter. The light plough and the light animals that pull it make it possible to exploit every interval between rains without causing excessive compaction of the soil. Weeds are controlled, though not very effectively; many weeds take root again fairly rapidly.

The seeds of *summer crops* are dropped into the furrow behind the plough, to be covered by the next passage of the plough, or else they are sown through a funnel attached to the frame of the plough.

This type of ploughing is the only tillage operation carried out; the work is arduous and slow. The period during which tillage is possible is strictly limited, the primitive plough being incapable of penetrating the soil when this has dried and become hard. For these reasons, the concept of the desirability of frequent tillage operations could not develop under these conditions, as it did in the temperate humid regions. On the contrary, traditional ploughing in the drier regions, as developed thousands of years ago, is more similar to the modern trend of 'minimum tillage' than to the concepts prevailing until quite recently in humid climates with developed agriculture.

In the summer-rainfall areas of monsoon Asia, the bulk of the farmers still use equipment that has remained unchanged for centuries. The principal instrument for ploughing, harrowing, puddling, sowing and intercultivation is the wooden stick plough, similar to that described above; other tillage implements are the hoe and

levelling plank. All these tools are produced by the farmers themselves or by local artisans.

In order to prepare a seedbed, using a hoe or stick plough, the monsoon farmer, like his counterpart in the winter-rainfall areas, must wait until sun-baked ground has been softened by rain; however, the onset of the rains is the most favourable time for sowing, so that the hand hoe farmer invariably misses the optimum time for planting. Lacking suitable equipment, he also cannot cope with workloads at other peak periods and as a result seedbed preparation, sowing and weeding are generally slipshod. To a lesser extent, this is also true for animal draught with primitive equipment. There is little place in this system for machinery, which can only be introduced after a complete change in the land use system.

The transition to modern methods

The composite picture that emerged by the beginning of the 20th century indicates a fairly good understanding of the objectives and effects of tillage: aeration of the soil, promoting increased availability of nutrients, better root penetration, weed control, breaking up compacted layers, etc.

The general attitude during the 19th century was therefore that the importance of tillage operations could hardly be overstated. This attitude, equating a maximum number of tillage operations with good husbandry, was further strengthened by the fact that the cost of upkeep of draught animals was practically the same, whether they were working in the field or were stalled; farm labour was also cheap and plentiful.

The importance formerly attached to cultivation as an objective per se, is vividly reflected in the following quotation from the *Standard Cyclopaedia of Horticulture*: "It would have been a sorry thing for agriculture if there had been no weeds. They make us stir the soil, and stirring the soil is the foundation of good farming" (Bailey, 1950). In short, weeds justify their existence simply by obliging the farmer to cultivate the soil!

It was only following gradual replacement of draught animals by tractors, that these traditional concepts of tillage were submitted to close scrutiny. For cost of tillage operations had become a substantial part of the overall production costs. Changes in the number and depth of soil cultivations could make possible considerable savings in production costs. Many experiments on the effects of tillage on crop production have been carried out since the beginning of the present century, and the results obtained were most surprising to the early investigators. The overall picture that emerged was that the need and justification for numerous tillage operations had been grossly exaggerated in the past. As a result of the objective re-appraisal of the effects of soil cultivation, a new understanding, new attitudes, and new methods, have evolved.

Modern conventional tillage

General objectives

Tillage objectives in semi-arid environments are *short-term*: such as land preparation for sowing and planting, improving the moisture régime in the soil, its nutrient status, and soil sanitation; seedbed preparation and weed control; or are *long-term*, such as preventing soil erosion and maintaining soil fertility. Some of these objectives overlap, such as an improved moisture régime and an improved nutrient status; others may be mutually contradictory, such as improving soil permeability for increased water retention on the one hand, and reducing evaporation to prevent water loss on the other hand.

The vast majority of beneficial tillage effects are very transient, and may disappear after a single, thorough wetting. Frequently, the only short-term effect, apart from weed control, is to create favourable conditions for sowing and crop establishment. Conversely, the harmful effects of tillage, such as soil compaction, are extremely long-lasting, if not permanent.

Improving moisture régime

The effects of tillage methods on crop growth and yields are to a large degree attributable to differences in soil moisture régimes which in turn are due to improved infiltration and conservation of water.

Water is lost by surface run-off, by infiltration beyond the root zone, through evaporation from the soil surface, and through transpiration by plants.

Tillage can be effective in reducing surface run-off if it is carried out according to approved soil conservation practices. These improve infiltration and may double the amount of water stored in the soil (Fig. 14.2).

The effect of tillage on moisture conservation will depend on the amounts and seasonal distribution of the rainfall. In seasons during which precipitation provides adequate water to the crop throughout the growing period, differences in soil moisture régime due to tillage have little or no effect on yields. Conversely, tillage methods that increase available soil moisture are beneficial to the crop in years of less than optimal rainfall. For example, in an investigation in tillage methods in Iowa (Amemiya, 1968), listed maize consistently out-yielded conventionally tilled maize in the six years that the crop showed signs of severe water stress out of eleven. The yield increases due to listing (which was conducive to water conservation) ranged from 308 kg/ha to as much as 2588 kg/ha; the average increase being 1524 kg/ha. In the other five years of the investigations, yields were above average because of favourable precipitation patterns, and there was little difference in yields among different tillage methods.

The effects of the tillage treatments were most marked in years in which there was

little soil-stored moisture at sowing time and when a large proportion of the early season precipitation occurred during the first six to seven weeks after planting.

Improving infiltration

Henderson (1979) points out that tillage practices that aim at maximizing infiltration generally increase evaporation from the upper soil (stubble mulching is an exception). It is therefore necessary to choose which objective is more important in accordance with circumstances. For example, in winter-rainfall areas with hot, dry summers, infiltration should be maximized; in summer-rainfall areas the only unequivocal choice is to achieve both objectives by a protective layer of crop residues (cf. p. 696). Unfortunately, in dryland farming, the amounts of crop residues left after harvest are frequently too small to have a significant impact.

Problem soils in relation to water infiltration are (a) heavy clay soils, especially when a high clay content layer is near the surface, and (b) soils containing frangipans, tillage pans, and clay pans.

Tillage per se may either increase or decrease infiltration. Tillage practices, such as loosening surface crusts, profile modification, deep ploughing, paraploughing, and vertical mulching can increase infiltration, enable deeper and more uniform soil wetting, as well as deeper root penetration.

Tillage may decrease infiltration when it smoothes the soil surface, reduces soil aggregation, eliminates surface residues, or causes compaction (Unger et al., 1983).

Contour furrowing for row crops is an effective water conservation practice. By combining contour furrows with level terracing, water can be stored in the furrows during most storms, while the terraces protect against erosion when the furrows overflow during heavy rains (Unger et al., 1988).

Another method for increasing water storage in the soil is basin listing (cf. p. 708).

Breaking crusts

Many of the soils in the dry regions, such as loess and vertisols, if unprotected by a plant canopy or mulch, form a crust under the beating action of raindrops, or as a result of slaking and breakdown of soil aggregates during wetting. These crusts are characterized by greater density, finer pores and lower saturated conductivity than the underlying soil. Once formed, a crust can greatly impede water intake by the soil (Hillel, 1971).

Soil crusting may affect seedling emergence, soil aeration and water infiltration (Unger, 1990).

When the crust prevents seedling emergence, it can be broken without damage to the seedlings, by special equipment developed for this purpose.

Preventing soil compaction

The heavy equipment used in modern irrigation farming, such as wheel tractors,

disks, subsoilers, and landplanes, etc., causes soil compaction, sometimes to a depth of 50 cm, and thereby adversely affects water penetration (Doneen and Henderson, 1953). This is accompanied by reduced root development and a striking reduction in plant growth.

In some cases compacted layers have been found to remain dry, even when the soil above the compacted layer is saturated with water. In these cases, waterlogged conditions above the compacted layer are an additional detriment to the crop (Raney et al., 1955).

In order to improve water infiltration and root penetration, compacted layers must be eliminated. This is achieved by tillage equipment which shatters the soil below the compacted zone. A depth of 30 cm is usually sufficient, but if the previous crop was harvested when the soil was still fairly wet, a depth of 50 cm or more may be necessary.

The effects of tillage on infiltration are very transient. Rainfall, irrigation, and cultural operations, compact the soil rapidly and the rates of water infiltration are soon reduced again to their former level.

The influence of soil compaction on loss of water by evaporation depends on the moisture content of the soil. At high moisture levels, conduction of water to the soil surface is greater in a compacted soil than in a loose one. When the soil surface is dry, however, water moves as vapour through the pore spaces, and evaporation will then be greater in a loose soil. Therefore, tillage may increase water losses due to evaporation by loosening the top layer of soil, but, by effectively destroying weeds, it may considerably reduce losses caused by transpiration (Fig. 14.2).

Paradoxically, in heavy soils, compaction may improve aeration; these soils tend to crack deeply on drying during the dry season; the deep fissures improve aeration to a considerable depth.

In brief, the net effect of tillage on moisture conservation depends on a number of factors including (Hillel and Rawitz, 1972):

- the duration of the process;
- the depth, degree and frequency of tillage;
- the influence of rainfall on reconsolidation.

Disposal of excess water

Heavy rains are frequent in semi-arid climates. On some soils it is necessary to provide for removal of excess water without causing erosion damage. Graded furrows are effective in conducting excess water from fields, preventing ponding, and avoiding soil aeration problems (Unger et al., 1988).

ICRISAT has developed a broadbed-and-furrow system which has been successful in improving drainage and soil aeration, while controlling erosion on Vertisols during the rainy season (cf. p. 715) (H.V. El-Swaify et al., 1985) (Fig. 4.11).

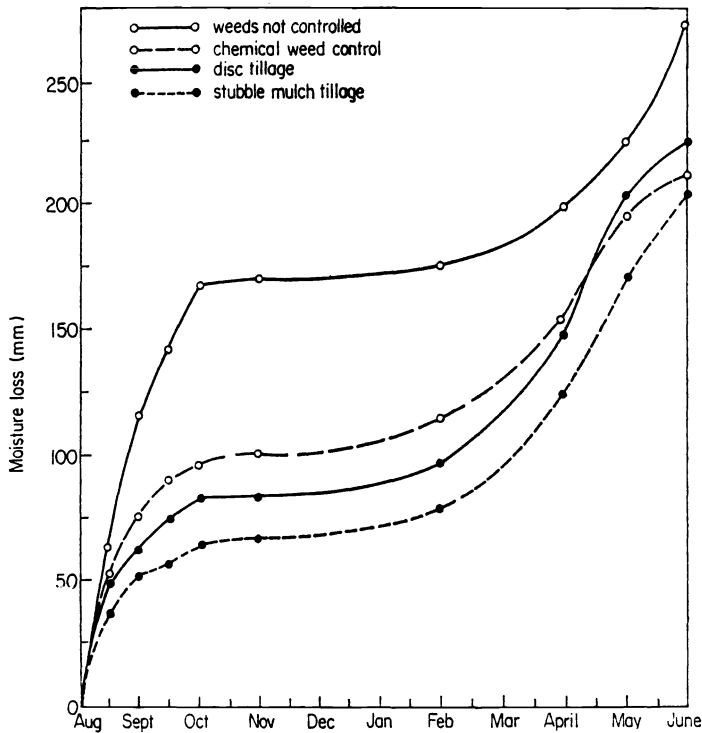


Fig. 14.2. Cumulative water losses under different methods of weed control and tillage, in the Great Plains region of the USA. From Wiese and Army (1958). By permission of the American Society of Agronomy, Inc.

Improved nutritional status

A direct relationship exists between the intensity of tillage and the nutrient status of the soil. The rate at which N is released from soil organic matter tends to be proportional to the intensity and frequency of tillage operations. Tillage promotes aeration and hence the decomposition of organic matter (provided moisture conditions are favourable). Air movement is usually satisfactory in soils with good structure; tillage can therefore improve aeration or impede air movement according to its effect on soil structure (see below).

Root penetration

Tillage usually affects only one-tenth of the soil volume in which the root systems of most crops develop, and therefore has only a limited effect on root penetration. Even subsoiling has not always been found to improve root penetration markedly. A plentiful supply of nutrients and soil moisture at the lower soil levels is considerably more

effective in promoting deep root penetration than tillage operations, unless a hardpan is present. In this case, its breaking up by ploughing or subsoiling is usually essential in order to improve root penetration (Fig. 14.3).

Soil sanitation

Tillage aims at improving sanitation by incorporating into the soil crop residues, weeds and volunteer plants, and thereby redistributing pathogenic organisms, weed seeds, insect larva and nematodes from the top soil, in which they are concentrated, to deeper layers of soil, and bury them at depths that prevent their attack on crops (Palti, 1981).

Soil drying

In the dry regions, a prolonged rainless period makes it possible to dry out the soil almost completely. The exposure of the top layers of the soil to strong radiation, and thus drying it thoroughly, has long been practised in warm climates to improve soil structure and as a means of sanitation. It is the only method cheap enough to be applied in extensive cropping (Palti, 1981).

Weischer (1977) has shown that drying the top soil layer by repeated and careful ploughing is fairly effective against rootknot and free-living nematodes. In the Middle East, it was the only effective method for eradication of perennial weeds, such as *Cynodon dactylon* and *Sorghum halepense*, before the advent of herbicides.

Palti (1981) describes the effects of thoroughly drying the soil and then rewetting on the weakening of the sclerotia of some major pathogens, such as *Sclerotinia* spp. and *Sclerotium rolfii*, until they are colonized and destroyed by soil micro-organisms.

The heat of the sun is not sufficient to dry the soil to the full depth of the rooting system, as the top layer, when once it has dried out, protects the lower layers. How complete drying-out is achieved will be described in the section on deep ploughing.

A more detailed analysis of the chemical, physical, and biological effects of soil drying will be presented in Ch. 16.

Modification of the soil profile

Microtopography. Microtopography refers to the surface configuration and roughness that remain after tillage (Renard and Fenster, 1983): depression roughness can store large quantities of detached sediment, greatly reducing erosion. However, as the depressions fill, erosion loss increases to a rate comparable to that from a smooth surface.

An uneven micro-relief may make it possible to store temporarily an appreciable amount of water during a rain or irrigation, so that it can later percolate into the soil. This transient storage capacity has been called 'depression storage' (Larson, 1962). Rough tillage methods, if done on the contour, could have a potential storage for a

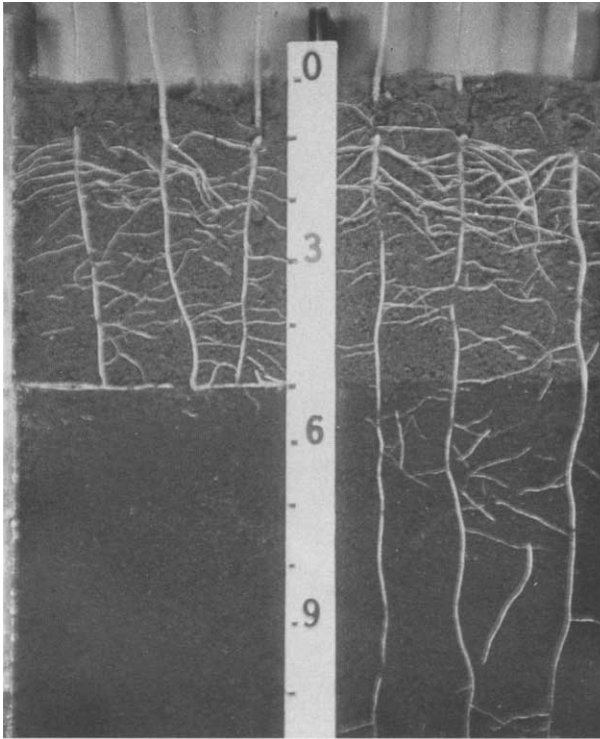


Fig. 14.3. Effect of soil compaction on depth of cotton root penetration. In the left-hand soil, a hardpan is present at a depth of 12.5 cm, impeding root penetration. In the right-hand soil, there is no hardpan and roots penetrate freely beyond the ploughed layer. Photo J. McKinney. From Flocker (1964). By permission of the American Society of Agronomy, Inc.

50 to 75 mm fall of rain, as compared to the 25 mm or less that can be stored with a smooth soil surface as usually prepared by conventional tillage practice (*ibid.*).

Soil inversion (see also 'deep ploughing'). The mixing and inversion of soil layers resulting from various tillage operations may alter the clay, silt and sand content within the tillage layer (Unger, 1990).

Under certain circumstances, soil inversion may be a desirable objective. It may bring to the surface fertile soil with good structure, covering the top layer that has lost its structure and is poor in nutrients. It may mix together surface soil and deeper layers which differ in texture, thereby improving the physical characteristics of the top soil.

Soil inversion may help to bury the seeds of weeds – particularly numerous in the top few centimetres of the soil – at a depth which effectively prevents their germination. It may help soil sanitation by a thorough burying of crop residues which may

carry insects at various stages of development or the spores of plant pathogens. For example, ploughing under the stubble of barley is an effective means of controlling the spread of barley stripe (*Helminthosporium* spp.), while burying the stubble of wheat prevents re-infestation by the wheat leaf-miner (*Scythris temperatella*). Complete incorporation of cotton stalks is a sanitary measure imposed by law in most cotton-growing countries, as an effective measure for controlling the pink bollworm (*Platyedra gossypiella*).

Soil inversion is not always beneficial; it may adversely affect plant growth and yields when it brings low-fertility materials or caliche and rocks to the soil surface, which obstruct plant emergence (Nunez et al., 1988).

Land levelling

Land levelling is of great importance in irrigation farming. Its purpose is to obtain an even distribution of water in the field. Water should be applied at intervals and in quantities that are calculated to restore the water content of the soil in the root zone to field capacity. This is impossible to achieve for the field as a whole, unless its surface is sufficiently level and uniform. Assuming that water is being supplied at the optimal rate, both high spots and low spots will reduce yields – the first receiving too little water, the latter too much.

Whilst careful and accurate levelling is essential for land that is irrigated by flooding or furrow irrigation, a reasonably even surface is also important when overhead irrigation is practised, as otherwise water will run off the high spots and collect on the low spots. Levelling must therefore be considered as an essential element in land preparation. Levelling operations should, however, be restricted to the absolute minimum possible; for as they have to be carried out in reasonably dry soil, there is a tendency for soil aggregates to be broken down by them, and for soil structure to be thereby impaired.

Weed control

Weed control is probably the most beneficial and universal role of tillage. Experiments have shown repeatedly that, on soils which have no special problems such as hardpans or excessive compaction, if they are free of weeds, crop yields are generally not markedly increased by tillage.

Tillage controls weeds by:

- (a) *preventing germination*: by burying seeds or by creating a cloddy surface;
- (b) *killing weeds*: with proper timing, it is possible to control weeds efficiently and economically when they are small, by using light equipment for cultivation. Alternatively, deep ploughing, carried out during the summer months in winter-rainfall areas, in dry soils, is a most effective means of control of perennial weeds such as couch grass (*Cynodon dactylon*) and johnson grass (*Sorghum halepense*);
- (c) *facilitating herbicide action*: some herbicides require incorporation with soil to

be effective. This is best achieved by soil mixing implements (disks, rotary tillers), rather than stirring or inverting implements (Unger, 1990).

Clean tillage and associated cultural operations

Clean tillage

Description. Clean tillage is a traditional approach that aims at achieving most objectives of tillage outlined in the previous section. Primary cultivation is generally based on the moldboard plough, which cuts and inverts a furrow, completely covering all crop residues, weeds, trash, volunteer plants, green manure and farmyard manure, and leaving a clean surface.

Subsequently, disking, cultivating, harrowing, and rolling, using a variety of implements, are needed to pulverize clods, compact the soil, destroy weeds, stir the plough sole, and prepare a smooth, clodless and firm seedbed.

Advantages. Besides being pleasing to the eye, clean tillage controls weeds effectively, facilitates seedbed preparation and sowing, in particular precision sowing; increases the rate of decomposition of organic matter.

Adaptation. Clean tillage was developed in the temperate climates of Europe, and later of North America, where it is still usually considered as the epitome of good farming.

In semi-arid areas, clean cultivation may be justified on flat lands, in areas with adequate rainfall; for small fields and for growing high-value crops under irrigation. It may be mandatory for monoculture of crops such as cotton, as an essential control measure against destructive insects that overwinter in the residues.

Depth of tillage

Increasing the depth of ploughing and other tillage operations has a very marked effect on costs: for every additional centimetre of increased depth, the amount of soil to be moved or turned is increased by about 150 t/ha! The enormous additional effort required cannot be accomplished without a considerable expenditure of fuel.

Much research, aimed at determining the most effective depth of tillage, has therefore been carried out – mostly in temperate climates. It was generally found that increasing the depth of ploughing beyond the minimum needed for a specific purpose – weed control, seedbed preparation, shattering a plough sole, etc. – did not improve yields.

Similar results were obtained in experiments in dry regions, when working with moist soil. Moisture conservation, an extremely important objective in dryland farming, is adversely affected by the depth of tillage – especially if the tilled soil layer is inverted.

“Moisture conservation varies inversely as the depth of dry soil at the surface,

when rainfall occurs” (Staple, 1964). As soils dry rapidly to the depth of cultivation, shallow tillage (up to 7 to 10 cm maximum) is less wasteful of moisture than is deeper tillage.

From a review of literature, Larson et al. (1983) come to a different conclusion, namely that deeper-than-usual tillage is mainly effective in increasing yields when water is a limiting factor and soil fertility is adequate. The favourable effect of deeper tillage was due to one or more factors, such as increased depth of rooting, improvement of water penetration, improved water holding capacity.

To test the hypothesis that deep tillage mitigates the effects of drought on crop yields, simulation runs were made by the authors on a silt loam, under compacted conditions (at 15 cm depth) and after shattering the compacted layer by a chisel plough. Mean yields were increased as deeper tillage increased the available water storage in the soil.

These results were obtained when water penetration was hindered by a compacted layer at a shallow depth and are therefore not surprising; otherwise, moisture conservation is generally adversely affected by the depth of tillage, especially if the tilled layer is inverted, as mentioned above.

The dry surface soil has to be wetted by rain to field capacity before any moisture can penetrate to at least 10–12 cm, at which depth it will be relatively safe from evaporation, and will contribute effectively to crop production. By avoiding tillage implements that invert the soil, subsurface moisture is not exposed and moisture losses are reduced.

Deep ploughing of dry soils

All the foregoing is relevant to the tillage of moist soils. The Mediterranean-type drylands are characterized by the seasonal complete drying out of the soil to the full depth of the root zone; this has no counterpart in temperate, continental, or humid tropical climates. Cultivation of completely dry soils, in general, and deep ploughing of such soils in particular, has specific objectives and specific effects.

Deep ploughing of completely dry soil, when carried out under the proper conditions, has marked beneficial effects that are difficult to achieve by other means: these effects – sanitation, improvement of soil structure, control of perennial weeds – are sometimes important in rain-fed agriculture and even more so in irrigation agriculture after several consecutive seasons of irrigation.

Procedures. In order to achieve the potential beneficial results from deep ploughing, the soil has to be completely dried out. The success of the deep ploughing depends, therefore, on the soil management during the year preceding the deep ploughing, and on the type of crop grown. The most desirable crop is a winter cereal that withdraws all the available moisture by the time it is mature. A reasonable amount of soil compaction during seedbed preparation and sowing of the winter crop is desirable, as it favours the formation of clods when the land is deep-ploughed in the

following summer. Deep ploughing should not start before the land has dried out sufficiently, but should not be too late in the season as otherwise the time available for drying and weathering the clods will be too short. At least three months between the completion of ploughing and onset of the rains (or irrigation) should be allowed for this purpose.

The depth of ploughing will vary from 50 to 70 cm – the lesser depth being for dryland farming, the greater depth for irrigated soils. This ploughing turns up huge, hard clods – a sight that temperate-zone farmers will find it difficult to associate with their traditional concepts of soil tilth! No attempt should be made to reduce these clods by cultivation. This is not only expensive and unpractical, but it will actually defeat the purpose of the ploughing. The clods must be baked by the sun and completely dried out. As a result, most parasites and pathogens are destroyed, and the rhizomes and other underground parts, of perennial weeds dry out and die. The weathering of the clods starts under the influence of superficial moistening by dew; their breakdown is, however, dependent on the first rains of the season or on irrigation – preferably by overhead sprinklers. The clods absorb the water like a sponge, whereupon the air that is trapped within the clods creates internal pressures and tensions which fissure the clods; after a short time these crumble down into a fine tilth, and a light tillage implement, such as a harrow or cultivator, is sufficient to prepare an excellent seedbed.

Improving water infiltration. Deep tillage can also fulfil an important role in improving water infiltration in problem soils (cf. p. 680). In particular those in which thin layers of slowly permeable clay or hardpans impede water and root penetration.

For example, Greb (1983) reports that deep ploughing (to a depth of 45 cm) an Aridic Paleustoll of the semi-arid Central Great Plains, containing a 12 cm thick argillic horizon at 10 cm depth, resulted in significant increases in soil moisture storage and consequent yields of barley as compared to shallow disk ploughing.

The use of chisels or paraploughs for deep tillage for improving water infiltration is less energy consuming than inversion-type implements such as moldboard ploughs. The former also leave crop residues on the soil surface, which also contributes to improved infiltration (cf. p. 698).

Profile modification. On certain problem soils, the objective of deep tillage is to modify the soil profile. For example, soils that are sandy on the surface are extremely erodible. If such a soil has a clay layer within 45–60 cm from the surface, deep ploughing can bring sufficient clay to the surface to increase cloddiness, which is very effective in wind erosion control. Though very expensive, the improvement achieved by deep tillage has shown to resist breakdown for several years (Johnson et al., 1983). Deep tillage and profile modification on the slowly permeable clay loam soil at Bushland, Texas in the early to mid-sixties, was still effective in increasing water infiltration rates in the mid-eighties (Eck, 1986).

Profile modification has been found to improve water storage and water use, with resultant increased yields on salt-affected soils (Eck and Unger, 1985).

These authors stress that soil profile modification increases crop yields only when it alleviates specific yield-limiting constraints.

Disease control. Deep tillage can also be an effective tool for disease control. For example, deep ploughing controls *Phymatotrichum* root rot of cotton, an otherwise difficult disease to control. The effectiveness of the treatment depends on inverting the soil with a fast-moving plough, soon after the crop is harvested, when the soil is relatively dry and no rain is expected.

A hardpan below the cultivated soil layer impedes the development of root growth of beans in California; subsoiling, by breaking up the hardpan, not only promotes root growth but also prevents severe damage from *Fusarium* root rot (Hanson et al., 1979).

Seedbed preparation and sowing

Seedbed preparation

One of the earliest functions of soil tillage was to prepare a seedbed and to cover the seeds. An initial ploughing is not particularly effective in this respect; it results in a too loose soil, with high evaporation losses. After it, seeds cannot be placed at uniform depth, contact between seeds and soil particles is not sufficiently intimate to ensure movement of moisture to the seed, and the seedbed dries out before the seeds have germinated. Seed emergence is therefore irregular, and stand establishment is incomplete. A number of additional tillage operations are usually needed to offset some of the negative effects of the ploughing – to break down the clods that have been turned up, to compact the soil that has been excessively loosened, to break up the plough sole, and to level the soil surface.

A well prepared seedbed, free from weeds, is one of the most important single factors in achieving a good plant stand and giving a good start to the crop.

A good plant stand, the density of which has been calculated in accordance with estimates of the environmental constraints likely to be encountered, is a basic prerequisite for successful production. The likelihood of satisfactory germination and seedling establishment is enhanced when the seedbed is well prepared with properly operated and suitable planting equipment.

A well prepared seedbed will provide adequate moisture, soil aeration, soil aggregate size relative to seed size, etc. It is not, however, the smooth, aesthetically satisfying seedbed favoured by temperate-region farmers that should be the objective. Only a small amount of moist fine soil is needed around a seed for germination; therefore most of the surface soil should be in hard clods. These resist wind erosion, help anchor mulches, slow run-off water, and provide physical shelter and shade for the young plants. They also impede the germination of weeds (Greb, 1983).

The large-seeded cereals should be sown at a maximum depth of 5–6 cm, and for small-seeded crops the depth should not exceed 2–3 cm (Johnson et al., 1983).

A seedbed should provide the essential conditions for good germination, and a favourable environment for the emerging seedling. These are, however, often conflicting requirements; thus a firm seedbed may be needed to ensure close contact between seed and soil, whereas a loose seedbed may be desirable for good aeration. The smaller the seed is, the greater will be its sensitivity to seedbed conditions and the greater the need for meticulous seedbed preparation.

Ploughing a too dry, too wet or compacted soil will leave many large, hard clods on the surface. Attempts to reduce these clods to a fine tilth by mechanical means, will usually result in a breakdown of the soil into dust, and the crusting of the soil surface after the first rain or irrigation.

In semi-arid and arid regions, the rapid drying of the soil surface favours the development of hard crusts which impede emergence. At the same time, because the soil dries so rapidly, the rate of seedling emergence assumes considerable importance.

Excessive packing of the soil surface will also increase the soil's crust strength and further impede emergence of the seedlings, thereby causing a spotty, unsatisfactory stand, and frequently resulting in a need for reseeding. Thus it has been shown, for example, that an increase in crust strength from 108 to 273 mbar results in a decrease in emergence of bean seedlings from 100% to nil (Richards, 1953). A light rain or irrigation will soften the clods and enable their breakdown by a single light harrowing or cultivation.

Insufficient compaction of the seedbed will leave many large airpockets in it, which interfere with germination and the root development of the seedling. On the other hand, excessive compaction impedes soil moisture movement and therefore reduces the moisture supply available to the seed. The poor aeration of an excessively compacted seedbed is also detrimental to germination. However, adequate compaction of the seedbed is effective in improving emergence, only if sufficient moisture for germination is available below the seed (Stout et al., 1961).

Time of sowing

All semi-arid regions have well-defined dry and rainy seasons; the onset, distribution and duration of rainfall are important considerations in the choice of sowing dates.

Timely sowing is extremely important. The dryland farmer faces a dilemma: if he sows in dry soil, shortly before the onset of the rainy season, he runs the risk that a light rainfall, sufficient to germinate the seed, but insufficient to keep the plants alive till the next rains, will make it necessary to resow. If the first rains are plentiful, problems may arise due to crusting or weeds, or both. If he waits for sufficient rain to ensure an adequately moist seedbed, he will then have to wait until the soil surface is sufficiently dry to allow the use of sowing equipment; the sowing itself is much slower and more laborious than on dry soil. The delay in sowing shortens the grow-

ing period, which is limited by the onset of hot dry weather, and results in reduced yields.

The risks faced by the farmer in rain-fed, semi-arid cropping, and his fears that the rains will not come in time, is poignantly expressed in the Bible: "He that goeth forth and weepeth, bearing precious seed..." (Psalms 126:6).

In India, deep Vertisols are traditionally left fallow during the rainy season because of the great difficulties encountered in seedbed preparation and sowing in the heavy, sticky soil, once the monsoon rains have started. Considerable run-off and erosion result during the rainy season from the bare soil.

Krantz (1981) reports that ICRISAT researchers have found that crops can be sown dry on these soils, shortly ahead of the monsoon rains, in areas where onset of rainfall is fairly reliable and there is a good probability of follow-up rains to ensure continued growth of the germinating crop. This discovery has greatly facilitated cropping the deep Vertisols during the monsoon season. Dry sowing is recommended only on Vertisols, which have a high water holding capacity, and for large-seeded crops (sorghum, maize, pigeonpeas, etc.) which can be planted relatively deep (5–7 cm). Small showers of 5–15 mm do not reach the seeds, and these do not germinate until about 25–30 mm of rain has occurred. This amount allows the seedlings to live without additional rain for about two weeks. A rainless period of two weeks after the start of the monsoon is expected at Hyderabad once in every 10–15 years. Dry sowing of Alfisols, which have a very low water-retention capacity, was found to be risky (Krantz, 1981).

In the Sahel, millet is frequently sown in dry soil before the rains. The early sowing generally ensures higher yields of grain, and provides more time for sowing groundnuts, which are sown after the first rains. Dancette and Sow (1976), on the basis of weather records, have estimated that dry sowing of millet would have resulted in the need to resow the millet eight times out of 44.

Bowden (1979) points out that it is possible to predict the chances of dry sowing, using long-term rainfall records, estimates of evapotranspiration and early crop water needs. An additional factor to be considered is the ability of the seedlings of certain crops, such as wheat and barley, to restart growth after partial desiccation and allow their tillering ability to compensate for missing plants.

The author's own experience, in a winter-rainfall area, confirmed by others in summer-rainfall areas (Dryland Agriculture Technical Committee, 1979) indicates that timely seeding in dry soil, in areas with adequate precipitation, provides sufficient advantages over waiting for adequate moisture in the seedbed, to be justified, notwithstanding the risks involved (Fig. 14.4).

After the seed germinates, drought may result in slow seedling growth, and as a result there is increased opportunity for the seedlings to be damaged by insects and diseases.

The date of sowing may have conflicting effects on plant diseases. An illustrative example is reported by El-Behadi and Al-Hassan (1979) with regard to sugar beets in

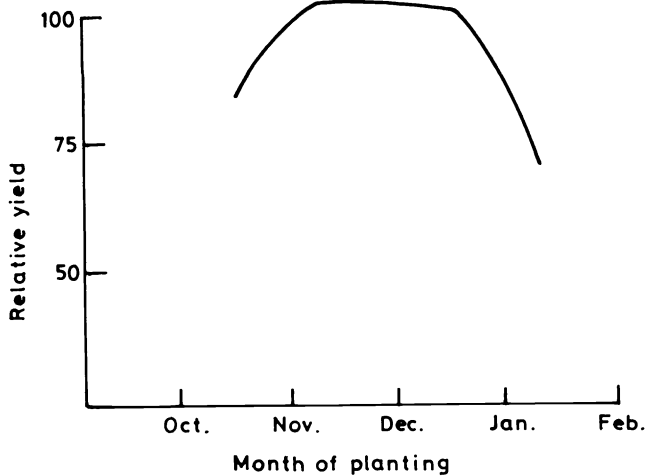


Fig. 14.4. Generalized relationship between wheat grain yield and time of emergence in a Mediterranean-type climate (winter rainfall régime). The sowing period for wheat (spring-type cultivars) extends from mid-October to mid-January. Earliest sowing is in dry soil, with attendant risks (see text). Optimal time of emergence is from mid-November to mid-December, ensuring long growing season and most efficient use of rainfall. Yields decline rapidly from January sowings because of unfavourable sowing conditions and shortened growing period.

Iraq. In early sowings, *Rhizoctonia solani* caused more damping-off than *Pythium aphanidermatum* or *Phoma betae*; the opposite occurred in late sowings.

In some cases, a delay in seeding may be indicated. In Israel, for example, early sowing of maize exposes the crop to attack by maize dwarf virus; sowing after mid-June ensures a virus-free crop. In Mexico, purple top wilt virus of potatoes is avoided by delaying planting from mid-March to early June (Hanson et al., 1979).

In seed crops, freedom from disease is a major consideration, more important even than yield levels. Sowing dates therefore have to be chosen so as to minimize the danger of infection by seed-borne systemic diseases. In semi-arid climates, most seed crops are sown at the time that ensures seed ripening during the dry season; this effectively prevents infection by almost all seed-borne bacterial pathogens, and reduces danger of infection by many fungal diseases (Palti, 1981).

Germination and crop establishment

The germinating seed and the young seedling have a number of requirements which make certain demands, that may be conflicting, on the desired character of the seedbed: these will now be considered.

Germination requires close contact between seed and soil particles, or otherwise water will not move rapidly enough into the seeds and germination will be delayed; free access of air to the germinating seed is also required, in view of the high oxygen requirements for the vital processes involved in germination and early growth.

The seedling must develop and reach the soil surface and light as soon as possible, to begin growth that will be independent of the nutrient reserves in the seed. The seed cannot be placed too deeply as otherwise its store of energy may not suffice for growth to the surface, and the seedling, if it emerges, will be weakened and hence unduly susceptible to attack by diseases and pests; nor can sowing be too shallow, or the seedbed may dry out too quickly to allow the seed to absorb sufficient water for germination. The development of the seedling will also be adversely affected, if its roots have to penetrate an excessively compacted soil, or large clods; numerous air-pockets are also detrimental.

Packing the soil at the surface may favour the formation of a crust and impede seedling emergence; it is therefore recommended to compact the soil at seed level, leaving the soil above the seed in a loose condition. This can be achieved, for example, by the use of a narrow press-wheel attached to the seed drill that presses the seeds into the soil, and then covers the seed with loose soil. The surface soil should not be broken down too finely, but left in a cloddy condition. Such a seedbed does not crust easily and water penetration into it will be satisfactory.

Planting equipment

Planting equipment should be capable of placing the seed at the right depth, at proper and uniform spacing, and ensure firm contact of the seeds with moist soil (Unger et al., 1988).

Small grains are generally sown with drills equipped with shovels, hoes or disk openers (Unger, 1983):

Shovel opener drills are used for sowing in moist soil overlain by a dry surface layer. They form ridges that help control wind erosion. They perform well in clean tillage systems and when residue cover is relatively sparse.

In the Pacific Southwest, three methods of sowing small-grain crops are commonly used: drilling, broadcasting by a drillbox without openers or from a plane on a prepared seedbed. The seed is covered by harrowing. Broadcasting is the most common method, but drilling produces a more uniform stand, with less weed problems and less lodging (Hatfield, 1983).

In dryland cereal-producing areas in the Pacific Northwest, sowing in dry soil is risky, because germination is dependent on when adequate rainfall will fall, and this may delay crop establishment beyond the optimum date; soil crusting may result in difficulties in seedling emergence. In order to avoid these risks, deep-furrow drills have been introduced, which makes it possible to place the seed into residual moisture from the fallow period, and thereby ensure crop establishment at the optimum time, without having to rely on timely rainfall (Bolton, 1983).

For row crops, lister planters are widely used for sowing in moist soil overlain by a fairly deep layer of dry surface soil. They are equipped with disk, shoe or shovel

openers. These open shallow furrows, by moving aside most of the dry soil layer, making it possible to place the seed in moist soil, at the desired seeding depth. The ridges help control wind erosion.

Planters (without lister openers) are used for sowing in moist soils, on flat-tilled land, on the ridges of lister-tilled land, and on irrigated land.

Inter-row cultivation

Inter-row cultivation is supposed to be beneficial by destroying weeds, by improving soil aeration, and by reducing losses of moisture from the soil.

Numerous experiments carried out in the field to determine the effect of inter-row cultivation on yields and on moisture conservation, have shown conclusively that the stirring of the soil was beneficial mainly in controlling weeds.

Creating a so-called *dust mulch* by pulverizing the soil surface by shallow tillage, in order to reduce evaporation “by disrupting the continuity of capillary pores to the surface” has been found to be ineffective, besides being ill-founded. By the time the soil has dried sufficiently to allow cultivation, most of the evaporation has already occurred. The tillage actually hastens the evaporation of the remaining moisture in the stirred layer. The need to repeat the operation after each rainfall increases the risks of erosion (Unger, 1984).

Besides weed control, inter-row cultivation may occasionally have additional beneficial effects. As a result of improved soil porosity, infiltration is increased and soil loss reduced after cultivating a crusted soil surface, such as usually forms after irrigation or heavy rainfall on certain soil types (Borst and Woodburn, 1942). Infiltration rates have been increased sixfold by loosening 0–8 cm of crusted surface soil (Duley, 1939). The best results are obtained when the rough configuration of the soil surface is preserved.

Improved nitrification in the upper soil layer, and somewhat lower temperatures in the loose soil, also result from cultivation, as compared with an uncultivated soil.

An important benefit from maintaining a loose layer on the surface of the soil is obtained on soils that tend to shrink and crack deeply on drying. Such cracks, which penetrate deeply, may cause the loss of considerable amounts of moisture throughout much of the root zone. In Texas, it was found that the evaporation from the side walls of shallow shrinkage cracks in a clay soil varied from 33 to 91% of that from a comparable area of surface soil (Adams and Hanks, 1964). These cracks are filled and covered by the loose layer that is formed during cultivation of the soil surface.

The general rule, nevertheless, is to keep the number of cultivations to the minimum required for weed control, and to cultivate at the most appropriate time for this purpose. Cultivation should be as shallow as is compatible with this purpose, in order to reduce damage to the roots of the crop as far as possible.

Newer concepts of dryland tillage

The failure of clean tillage

The traditional methods of tillage, developed in the temperate moist climates and based on the moldboard plough, when applied indiscriminately in dryland cultivation, have frequently had disastrous effects, mainly by increasing erosion.

Under the conditions of limited rainfall of drylands, maintaining a weed-free fallow was considered essential to accumulate sufficient moisture in the soil for the cereal crop. The traditional tillage methods used for this purpose involved seven to ten operations per season, beginning with ploughing in spring, followed by shallow tillage implements throughout the fallow period. Fallow efficiencies ranged from 16 to 22% (Greb, 1983).

In spite of the numerous functions of tillage described in previous paragraphs, modern agricultural science views tillage, at best, as a necessary evil. Among the negative effects of tillage (some of which are interrelated) are the following: breakdown of soil structure, soil compaction, increased erosion, impaired soil aeration, lower levels of organic matter, reduced infiltration, and water ponding on the soil surface.

Several of these issues have been treated in different sections of this chapter.

The frequent cultivations needed to keep the fallow weed-free, and to conserve moisture, pulverized the surface soil and buried all crop residues; the degraded and unprotected top soil was then easily eroded by wind and rain.

The best-known example of the disastrous effects of this approach to farming in a semi-arid environment was the 'dust bowl' of the central USA, which resulted from ploughing up the original prairie for the growing of cereals, and which has been defined as "the most serious man-made environmental problem the USA has ever seen" (Lockeretz, 1978).

The traditional concept of 'clean' cultivation, in which the farmer equated good farming practice with the complete burying of crop residues and weeds, had to be abandoned. Instead, a new approach was developed, which aimed at keeping the soil protected at all times, by leaving crop residues on the soil surface, during the periods between crops and during crop growth. This new concept also includes minimizing tillage in order to prevent excessive soil compaction by farm machinery, save energy and labour costs, and maintain a favourable soil structure. The logical outcome of attempts to minimize tillage, is no-tillage, a concept that has become feasible by replacing tillage by herbicides.

The new tillage concepts were initiated and developed in the semi-arid regions of the USA.

TABLE 14.1

Changes in tillage methods (1915–1977) and their effect on fallow efficiency at Akron, Colorado

Tillage system	Years in use	Tillage operations	Fallow efficiency ^a (%)
Maximum tillage			
Plow and harrow	1915–30	7 to 10	16 to 22
Conventional bare			
Shallow disk, rodweed, or harrow	1931–45	5 to 7	20 to 24
Modified conventional			
Disc (once), chisel, rodweed	1946–56	4 to 6	24 to 27
Stubble mulch			
Sweep, rodweeder	1957–70	4 to 6	27 to 33
Minimum tillage			
Herbicide replaces one or more tillages	1968–77	2 to 3	33 to 38
No-till			
Herbicides only	1975–	0	45 to 55

^aDefined as the percentage of precipitation stored in the soil during the fallow season.

Source: Greb et al. (1979).

Changes in tillage systems in the US

Greb et al. (1979) have described the changes that have taken place in the approach to tillage methods for dryland areas in the US. These changes and their impact on precipitation storage in the soil are shown in table 14.1.

*Conservation tillage**Description and importance*

Conservation tillage has been defined as any tillage and planting system in which at least 30% of the soil remains covered by crop residue after sowing (Whyte, 1987). Various types of conservation tillage have evolved, differentiated mainly by the amount of crop residue and the number and nature of the tillage operations. Different systems have evolved for small grains, such as stubble mulch farming, minimum tillage and no-tillage; and for row crops, such as zone tillage.

Conservation tillage was first developed for large-scale mechanized crop production in semi-arid regions in the USA, Canada, Australia, etc. The success of these methods in the USA, for example, is evidenced by the increase in the percentage of

cropping area on which conservation tillage is used in the period 1963 to 1986, from 1% to 36% in the Northern Plains, 20% in the Southern Plains and 19% in the Pacific region (Conservation Tillage Information Centre, 1988).

Conservation tillage is now one of the most widely used conservation practices in the United States for rain-fed farming. Adoption has been much slower on furrow irrigated land because farmers were concerned that the crop residues would retard irrigation flows and cause irregular distribution in water coverage between upper and lower parts of the field. Research has shown, however, that the practice has the same advantages for irrigation farming as for dryland agriculture in reducing erosion and improving moisture conservation; the number of irrigations and total water use are also reduced. Concern on water coverage was found to be unfounded (Magleby et al., 1985).

More recent studies have shown that the underlying principles of these methods for conserving soil and water are applicable in the less developed countries, where hand or animal-drawn equipment is used (Unger, 1990).

Stubble mulch tillage

Description

Stubble mulch tillage was first developed as a wind erosion control measure by a coordinated research effort aimed at avoiding a repeat of the disastrous 'dust bowl' calamity of the 1930's in the central USA (Zingg and Whitefield, 1957). Instead of clean tillage, crop residues are left on the soil surface by using sub tillage equipment for loosening the soil and controlling weed growth. Experience subsequently showed that stubble mulch farming was not only an effective wind erosion control measure, but had additional advantages (described in the next section), which made it eminently suitable for large-scale rain-fed crop production in semi-arid areas.

Hill (1990) stresses that changes in soil physical conditions due to the change-over from conventional inversion ploughing and attendant tillage operations to conservation tillage develop slowly. Voorhees and Lindstrom (1984) found that 3 to 4 years were required before soils under continuous conservation tillage developed improved porosity in the upper soil layer (0–15 cm) after years of moldboard ploughing.

The role of crop residues in conservation tillage

Dryland systems in which crop residues are removed or burned, ultimately lead to severe soil deterioration and loss of fertility. Various methods of conservation tillage have been developed, all of which are based on stubble mulching, i.e., retaining crop residues on the soil surface.

Because mulching with residues is the one common component of all conservation tillage methods, we will first discuss the implications of maintaining a surface cover of crop residues.

Favourable effects

Establishing or maintaining a crop residue mulch on the soil surface usually increases soil water content through improved infiltration and reduced evaporation.

Reducing run-off and erosion. The mulch dissipates raindrop energy, minimizes crusting of the soil surface, retards run-off, and improves infiltration; soil and water erosion is thereby reduced.

Maintaining a soil cover has been shown to be the most effective single factor for reducing erosion by both wind and water: a 90% mulch cover was found to cut erosion by 93% (Wischmeier and Smith, 1978) (Fig. 14.5). Associated with decreased erosion is a cleaner environment, with less dust in the air and sediment in the water courses (Unger, 1990).

In experiments in Nebraska it was found that the rates of erosion of a mulched

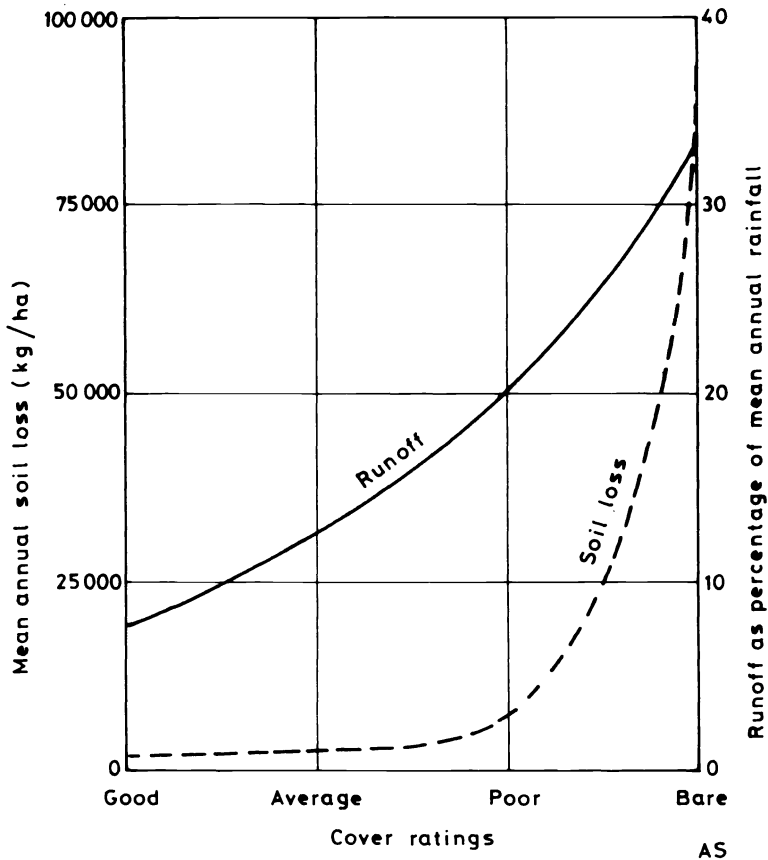


Fig. 14.5. Run-off and soil loss on arable land for different crop-cover values. For sandy-clay loam on 4.5% slopes, average of five years. Good cover rating corresponds to high-density maize, average corresponds to medium-density maize and poor to late planted legumes. From Elwell and Stocking (1976).

surface were about one-fifth of those resulting from 'clean tillage' with moldboard ploughing (Zingg and Whitefield, 1957). Wind erosion was also substantially reduced: residues of various amounts, types, and orientation, reduced the force of the wind immediately above the soil's surface by from 5 to 99% (Zingg, 1954). The crop (and weed) residues left on the surface of the soil not only offered protection against erosion, but improved water penetration and reduced losses from evaporation.

In a three-years grain rotation in Nebraska, a clean-ploughed loess soil lost two to six times as much run-off water and four to eight times as much soil by erosion as did stubble-mulched land (Duley, 1960).

Within certain limits, the control of run-off and erosion is proportional to the amounts of crop residues left on the soil's surface; small amounts are more effective against wind erosion than against water erosion (Zingg and Whitefield, 1957). When the total straw production of the crop does not exceed 1 t/ha, very little protection can be expected from the residues left on the surface (Luebs and Laag, 1964).

Mulches can be maintained on the soil by stubble mulch tillage, or by using herbicides to control weeds (Unger et al., 1988). The mulches have been found to be most effective and beneficial in regions and seasons of low rainfall, and are critically needed where wind erosion presents a considerable hazard. Under conditions of higher rainfall, negative results have been reported; apparently, the stubble mulch was conducive to excess moisture, with resultant ill effects.

Reduced evaporation. Evaporation from the soil can be reduced by maintaining a mulch cover. The effectiveness of the mulch in reducing evaporation is dependent, among other factors, on the thickness of the mulch (cf. p. 704).

Low-density residues, such as wheat straw, reduce evaporation much more effectively than higher-density materials, such as sorghum stubble or cotton stalks. Therefore, about twice as much sorghum residues, and four times as much cotton stalks are needed to obtain the same degree of reduced evaporation obtained with wheat straw on a weight basis (Unger, 1990).

Mulches retard evaporation from recent rains, and thereby provide seeds with a better opportunity to germinate and the seedlings with a better chance to establish themselves. Mulches can also enhance internal drainage to greater depths where it is less likely to be lost by evaporation (Hillel and Rawitz, 1972).

Improved soil moisture. Improved water conservation is the net result of reduced run-off and reduced evaporation due to mulching.

Greb (1983) summarized the results of long-term experiments for four locations in the US Great Plains on the effect of crop residue mulches on soil moisture. In most cases the cropping system was wheat-fallow. The mulches increased soil water significantly, and the increase was roughly proportional to the amounts of surface residue over the range of 2.2 to 6.6 t/ha. Each t/ha of crop residue saved about 9 mm of water.

In Texas, Unger (1978) found that a 1 t/ha mulch of wheat straw increased soil water during an 11 month fallow by 36 mm; at 4 t/ha an additional 12 mm were saved per ton of residue. In the US Northwest Pacific (winter rainfall), the amount of water saved during a 12 months fallow was 4 mm/t of residue.

In a semi-arid area of the USA, soil moisture content at sowing was 13% higher under stubble mulch compared with clean tillage, and wheat yields were 17% higher (Johnson and Davis, 1972).

In Nigeria, soil under different crop residues, retained 2.1 to 5.8 percentage units more plant-available water than bare plots (Juo and Lal, 1977).

The improved moisture régime under mulching is favourable for microbial activity over longer periods of time, resulting in increased size and duration of microbial biomass and greater amounts of N temporarily immobilized in this biomass (see below). Thus, the greater microbial biomass in the surface of mulched soils contributes nitrogen at a controlled rate to the crops (Power and Doran, 1988).

Research in the USA, Canada and the former USSR has shown that soil moisture can be increased significantly by stubble management for improved snow retention, and that this increase can, in one winter, equal the gains in soil water from summer fallow (Snyder et al., 1980). Effective management techniques for snow retention are: tall stubble; alternating stubble heights; use of 15 m wide strips of standing stubble (Papendick et al., 1980).

Improved nutritional status. Rasmussen and Rohde (1988) report that stubble-mulch tillage resulted in the retention of 6 kg more N per hectare per year than bare tillage after 44 years in a wheat-fallow rotation. They also found that 18% of the fertilizer N applied during this time could be accounted for in increased soil organic N, in particular in the upper 75 mm of soil.

Reducing salinity. Mulches have also been found effective in reducing salinity. Thus low precipitation, high evaporation, high water tables, and a compacted soil, generally cause salt increases in the upper soil layer under bare fallow. Seasonal precipitation has to be in excess of 250 mm to reduce salinity. Using a straw mulch was found to result in appreciable reduction in salinity, even with below-normal precipitation (Benz et al., 1967).

Soil temperatures. Surface residues significantly affect soil temperatures, mainly by changing the radiant energy balance of the system. The radiation balance is influenced by reflection of incoming radiation by the residues, heating of soil and air, and evaporation of soil water (Van Doren and Allmaras, 1978).

The changes in water content and aeration due to tillage affect the soil temperature régime. The greater amount of water in no-tilled soils, and the slower rates of gaseous exchange, result in less variation in diurnal temperatures. The insulating effects of the mulch can also reduce mean daily temperatures by 2 to 4°C. These reductions in soil

temperature and the concurrent effects on biological activity can be favourable or unfavourable for crops, depending on climate, soils, and season (Power and Doran, 1988) (cf. p. 78).

In cold weather, mulched soil is usually warmer than bare soil, because of the insulating effect of the mulch. The insulating effect increases with increasing mulch thickness (Unger, 1990).

Problems associated with residue mulches

Reduced soil temperatures. For a period of three to six months after applying a straw mulch of 5–8 t/ha, soil temperatures were reduced by as much as 3 to 6°C at a depth of 2.5 cm, and by 2 to 4°C at a depth of 10 cm (McCalla and Duley, 1946).

The lower temperatures may have adverse effects in cool locations with relatively short growing seasons, by delaying crop establishment (Unger, 1990). Aston and Fischer (1986) reported that cooler temperatures associated with high residue levels at sowing reduced early season growth of wheat in southeastern Australia.

Sanitary problems. Mulches may harbour disease pathogens and pests, and one of the traditional justifications for clean tillage has been to help control crop enemies. Considerable research has been devoted to investigating the effect of mulches on crop pests, but the results of different studies have generally been contradictory or non-conclusive (Unger, 1990).

Diseases: Cook et al. (1978) mention the following ways in which crop residues can affect crop diseases: (a) by providing the pathogens with food, and a favourable environment to live and reproduce; (b) by affecting the physical environment of the host plants; and (c) by intensifying microbial activity in the soil with the resultant production of decomposition products which may affect the pathogens, the susceptibility of the host plants, or both.

The same authors explain the apparent contradictions mentioned by Unger (1990), by stressing that the effects of tillage on disease in one area may be completely different to those observed where environmental conditions are different. Among the many examples given by these authors: reduced tillage, by conserving soil moisture, reduces *Fusarium* stalk rot of sorghum grown in summer in western Nebraska, and has the opposite effect on *Fusarium* root rot of wheat grown in winter in the dry areas of Washington and Oregon (Cook et al., 1978).

In relation to crop diseases, Palti (1981), citing unpublished material from Yarham and Norton, concludes that “with the exception of *Septoria* blotch, persistence of pathogens on wheat stubble aggravates the incidence of wheat diseases less than might have been expected”. Chemical control of most wheat diseases is now possible, and therefore the role of pathogen persistence is no longer a major consideration when stubble mulch is economically beneficial (ibid.).

Insects and other pests: Musick and Beasley (1978) report that the transition to conservation tillage has generally increased pest problems and elevated certain ani-

mal problems (such as armyworm, stalk borer, slugs and rodents) to major pest status. However, other pests, such as the lesser corn borer have become less important. Overall, many pests will continue to pose the same threat to maize, for example, in conservation tillage as in conventional tillage.

The herbicides used in reduced tillage practices have also eliminated the natural hosts of some insects, forcing them to feed on crop plants (Gregory and Musick, 1976).

In the case of some insects, stubble mulch may actually help to control them. The greenbug (*Schizaphis graminum*), a major pest of sorghum, is repelled by light reflectance of straw residues, and greenbug populations were significantly lower in sorghum planted in stubble mulch than under clean cultivation (Burton et al., 1987).

Gregory and Musick (1976) summarize the pest problems of conservation tillage by stating that insects are not an "insurmountable problem to reduced tillage cropping systems".

Problems with birds and rodents are usually more severe with conservation tillage, especially no-tillage, than with clean tillage; for these pests, the crop residues provide a favourable habitat. Hence the need to regularly observe the crops to determine whether pests are present and to take whatever measures are necessary (Phillips, 1984).

Weeds: Control of weeds is often difficult with conservation tillage. Williams and Wicks (1978) postulate that "a specific control of weedy vegetation is generally less effective as the tillage decreases. In particular, the transition from moldboard ploughing to no-till systems increases the potential for perennial species".

Unger et al. (1988) point out that weed control under stubble mulching is most deficient when the tillage is done while the soil is moist or when it rains shortly after tillage. For example, a small rain of 3–4 mm, received within a few hours after tillage, enables weeds to re-establish themselves.

Improved weed control is possible by replacing some of the tillage operations by chemical weed control.

Phytotoxic substances: these may be produced by micro-organisms when surface residues are increased (Elliott et al., 1978). Soon after the introduction of stubble mulching, it became evident that in some years poor wheat stands were obtained and plants from high-residue areas were smaller than those with low amounts of residues. Crop yields were reduced by the microbial decomposition of the residues, and it was assumed that the production of short-chain aliphatic acids (acetic, propionic and butyric) were at least partly responsible for the problem (Lynch, 1983).

In a review of phytotoxicity associated with residues, Elliot et al. (1978) conclude that available evidence strongly implies that phytotoxins are responsible for wheat yield decreases resulting from surface residues. These authors recommend avoiding direct or near-direct contact between residues and seedlings, by managing crop residues away from the seed row. Placement of the residues between the rows would have the additional benefit of inhibition of weed growth by the phytotoxins.

Residues produced in excessive amounts, can accumulate in soils because microbial decomposition is suppressed by increased loading rates. At excessively high loading rates, anaerobic conditions could occur even at the soil surface. Hence the similarity in the processes that occur in soils that receive heavy loads of crop residues or organic wastes compared with poorly drained or waterlogged soils (Parr and Papendick, 1978).

Nitrogen immobilization. A further reason for problems due to residue-mulching is that the high C/N ratio of the crop residues may depress nitrification especially in the early growth period and thereby adversely affect the growth of the crop and, ultimately, its yield.

Research data appear to indicate that the response to stubble mulch tillage is intimately linked with nitrogen availability, as is indicated by the greater response to nitrogen of cereals growing on stubble mulch tilled plots as compared with conventional tillage, and also by the reduction in protein content of the grain and the reduced straw production of mulched plots. Soil analysis also showed reduced nitrates under stubble mulching (Luebs and Laag, 1964).

The lower rate of nitrification under stubble mulch, as compared to 'clean tilled' plots, may be due to lower temperatures, to less effective aeration, and most impor-

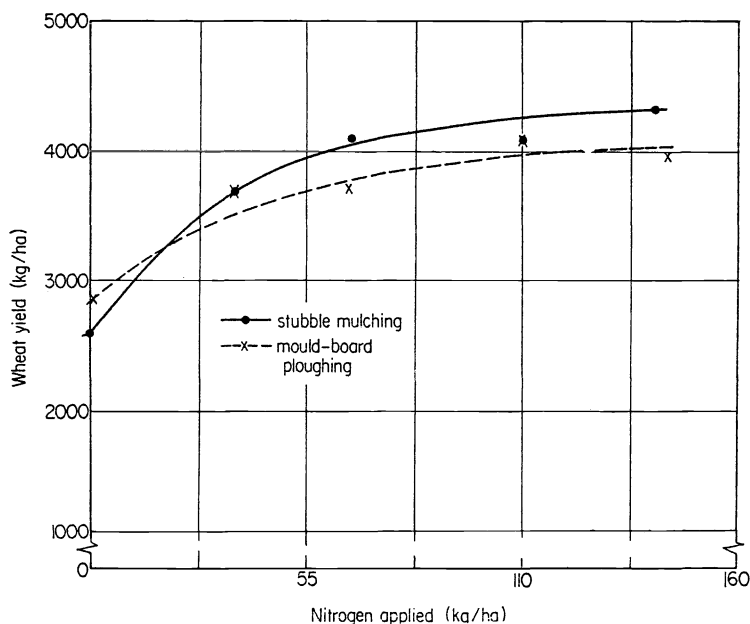


Fig. 14.6. Average trend of wheat yields under stubble mulching and moldboard ploughing in relation to amount of nitrogen applied. Note that stubble mulching gave superior yields to moldboard ploughing only when adequate amounts of N were applied. From Zingg and Whitefield (1957). By courtesy of the US Department of Agriculture.

tant, to nitrogen fixation by the crop residues, which decomposed more slowly on the soil surface than when incorporated in the soil (Figs. 14.6 and 14.7).

The obvious conclusion to be drawn from these observations is that a favourable effect from stubble mulching can be expected only if nitrogen is applied in the quantities and at the times required to offset the negative effect of mulch on available nitrate supply.

Effect of mulches on yields

On the whole, the favourable effects of mulching outweigh the disadvantages outlined above, and yields are generally improved. Overall, conservation tillage systems generally have greater favourable effects on crop production when carried out on soils with low organic-matter levels and poor structure than on soils with high levels of organic matter and a good structure (Kladivko et al., 1986).

Increased crop yields are due to the more favourable soil moisture régime under crop residues, more efficient nutrient availability and cycling, and the decrease in soil erosion (Smith and Elliott, 1990). As a rule, water conservation and crop yields increased with increasing amounts of residue maintained on the soil surface (Unger, 1990) (Fig. 14.8).

From a review of reduced tillage and residue management effects on soil fertility, Smith and Elliott (1990) conclude that these two management tools can substantially increase crop production in semi-arid areas.

The overall effects of conservation tillage are influenced by soil properties and by

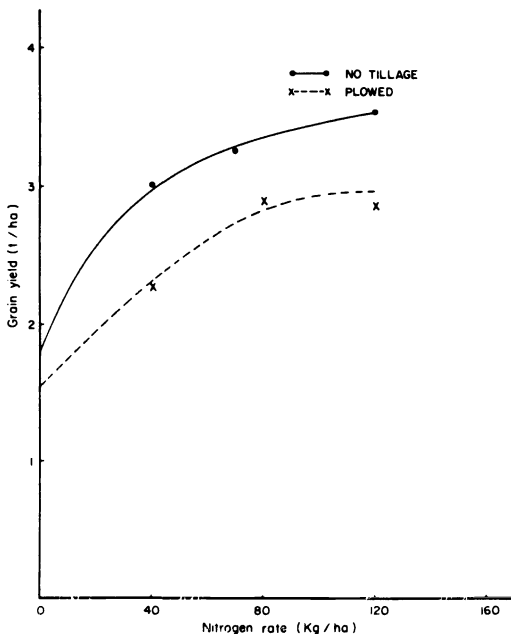


Fig. 14.7. Nitrogen response of maize for two tillage systems for an Alfisol. From Lal (1986a,b). By permission of Springer, Berlin.

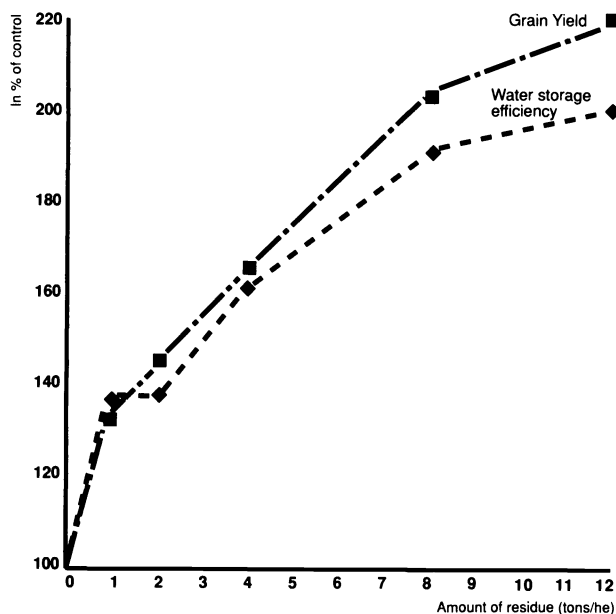


Fig. 14.8. Influence of residue levels on soil water storage at the end of fallow period (average for four Great Plain locations). Control (no residues): water storage efficiency 22.6%; grain yield = 1780 kg/ha; average water storage to 1.8 m depth = 318 mm. Based on data from Greb et al. (1979).

specific crop and environmental relationships, and therefore management practices, for maximum benefit, must vary from the semi-arid steppe to the semi-arid tropics and should be adapted on a regional basis (Smith and Elliott, 1990).

Conservation tillage has been less satisfactory than clean tillage under the following circumstances (Unger, 1990): on poorly drained soils; where extremely large amounts of residues are present, causing problems of weed, disease and pest control; where residues are insufficient to cover the soil adequately; and where the soil is eroded or strongly degraded.

On soils that have been eroded to the C horizon, the soil structure can be so poor that roots will not penetrate into the lower soil horizon. For these problem soils, Smith and Elliott (1990) recommend a special treatment: soil loosening, with deep phosphate and sulphur placement to allow and encourage deeper rooting, direct drilling, return of crop residues, and inclusion of a legume in the crop rotation.

Quantities of surface residues

The amounts of residue on the soil surface directly influence soil water storage during fallow, as shown in Fig. 14.8.

Generally a mulch consists of crop residues from the previous harvest. Small amounts of residues are ineffective as mulches; under these conditions it is possible to

increase the amount of crop residues by the planting of cover crops. These also provide protection against soil erosion and utilize residual soil nitrates, thereby reducing the potential for losses by denitrification and leaching (Power and Doran, 1988).

Mulches in the semi-arid tropics

In tropical regions, most residues are used for fuel, fodder; or are burned off; the remainder decomposes rapidly. To provide cover, crop residues from outside sources are frequently introduced to serve as mulch, or cover crops are grown. Residues from various tropical legumes grown as cover crops may add 6.5 to 13.0 t/(ha year) organic matter. Using reports from various sources, Power and Maskina (1988) conclude that such mulches can improve the organic matter status of tropical dryland soils, reduce erosion, improve soil physical structure, and crop yields. In India, mulches of sugarcane and pearl millet stalks reduced maximum soil temperatures and increased yields of spring-planted tubers. In Punjab, organic mulches increased soil moisture storage, resulting in higher yields of maize and wheat.

Equipment for stubble mulching

Stubble mulch tillage presents practical problems: the residues left on the surface interfere with seedbed preparation, weed control and sowing operations. The traditional tillage and sowing equipment are not suitable under these conditions, and a whole new class of equipment had to be developed before the new system became practical. Subsurface cutting implements were developed which loosen the soil and cut the roots of weeds, leaving the residues on the surface as undisturbed as possible. The typical tillage implement for this purpose is the 'sweep cultivator', the sweeps consisting of large inverted V-shaped blades, attached to a cultivator frame and operating parallel to the soil surface at a depth of 10–15 cm. The sweeps slightly lift and shatter the soil.

Large, high clearance V-blade implements have been specially developed for stubble mulch tillage, and are used in combination with increased tractor power.

For mechanical weed control, the two main types of implements used are the 'blade cultivator', with a single blade on a two-wheel carriage, and the 'rodweeder', in which a slowly revolving horizontal rod, operating at a depth of 10 cm or more, rotating counter to the direction of travel, compacts the subsurface and moves clods and weeds to the surface.

When properly used, in previously well-prepared fallow, the rodweeder fulfills the purposes of summer tillage in an economical manner.

Several variations of the rodweeder, to fit different soil conditions, have been developed, such as shovel attachments or semi-point chisels, mounted ahead of the rod, to aid in soil penetration.

It is possible to combine sweep cultivation with rodweeder operations if necessary.

A sweep or field cultivator may be used early in the summer tillage operations,

followed by the rodweeder in late summer or early autumn (Dryland Agriculture Technical Committee, 1979).

When crop residues exceed 4.5 t/ha, a disk-type implement may be used for one or more tillage operations to reduce the stubble to a manageable quantity (Fenster et al., 1977).

Regardless of type, each tillage operation reduces the amount of residues on the soil surface. When the amount of residue is less than 4 t/ha, it is important to keep the number of tillage operations to the minimum required to control weeds. Even subsurface tillage reduces the quantities of surface residues (about 50% reduction after four operations) (Anderson, 1961).

The paraplough is a tillage implement that leaves most crop residues on the soil surface. From the limited data available, Unger et al. (1988) conclude that paraploughing has potential for conserving soil and water on dense, high-clay soils, by maintaining surface residues and improving infiltration rates.

Seedbed preparation. If the procedures described above are followed, an optimum seedbed will result. The soil will be covered by crop residues and many large clods, both required to reduce erosion and ensure an adequate moisture supply for seed germination and plant establishment (Hinze and Smika, 1983).

Special planting equipment. Specially adapted disk-opener drills with larger than usual disks spaced wider than on the conventional drills are satisfactory for seeding when there are large amounts of residues on the soil. They are however not very good for penetrating dry seedbeds and often result in a low germination rate of wheat seed (Greb, 1983).

Hoe-type drills perform better than disk-opener drills in stubble-mulched fields. High-clearance, deep-furrow hoe drills, with row spacings of 25–35 cm, are adapted to seeding in drier soils and in stubble mulch residues. The hoes can penetrate dry surface layers and place the seed into moist soil. A press wheel firms the soil around the seed, ensuring good germination. The furrow provides protection to the emerging seedling from wind and blowing soil (Jones et al., 1990).

A recent development for seeding in stubble mulch is the air seeder, in which the seed is metered and carried by an air current from the seed hoppers and placed behind point or sweep openers into the seed row. Press wheels for each row ensure a good contact of the seed with the soil.

Air seeders operate through residues without plugging. Machines of up to 20 m width can seed large areas rapidly (Jones et al., 1990).

Subsoiling and 'vertical mulching'

Subsoiling

There are many cases in which soil inversion – the typical function of the plough in

temperate regions – is unnecessary, and sometimes undesirable. For example, when a soil has been carefully levelled for irrigation, conventional ploughing will undo much of the levelling. After ploughing, it may become necessary to disk and land-plane the field in order to re-establish the level surface required; these are costly operations and also pulverize the soil excessively. In irrigation farming, on land that is reasonably clean of weeds and crop residues, ploughing can frequently be replaced by ‘subsoiling’, e.g. loosening the soil to an appreciable depth without inversion. The subsoiler consists of 2 or 3 strong vertical shanks, with chisels, mounted on a cultivator frame, operating to a depth of 60–70 cm, that cut a narrow slot through the soil, and shatter the subsoil. Subsoiling is probably the most effective method of breaking up compacted or cemented layers and thereby improving root penetration, aeration, and water penetration. To be effective, it must be done in dry soil. If the subsoil is wet, instead of the desirable shattering effect, the soil will smear and become compacted along the track of the subsoiler shanks.

Vertical mulching

Unfortunately, the effects of subsoiling are not long-lasting, the slots left by the subsoiler closing and becoming sealed off within a few months. In order to prolong the beneficial effect of the subsoiler, a method called ‘vertical mulching’ has been developed. The object of this is to fill the slots with organic material and thereby keep them open and functioning for longer periods. By modifying a conventional subsoiler and attaching a flail-type chopper to the unit, suitable organic material is chopped and introduced into the slots that are opened by the subsoiler. It was found that only dry carbonaceous material that decomposed slowly, such as cereal stubble, maize stalks, corn cobs, cotton burs, wood chips, etc., was suitable (Spain and McCune, 1956) (Fig. 14.9).

For vertical mulching to be effective, the compacted layer with low permeability must be sufficiently shallow to be shattered by the subsoiler, and there must be a permeable layer under the compacted layer (Curley et al., 1959).

Vertical mulching, at intervals of 4 and 8 m has increased soil water recharge and crop yields in India (Rama Mohan Rao et al., 1977). Gypsum-enriched slots are being tested in Australia (Jayawardane and Blackwell, 1985).

A more recent form of vertical mulching, called ‘slot mulch’ has been developed for control of erosion and run-off during heavy rains on soils of low permeability. The approach is to compact residues of a cereal crop into a narrow continuous slot, about



Fig. 14.9. Slot mulch combined with raised beds. For soils of low permeability.

5–10 cm wide and 20–25 cm deep, cross slope, with the soil ridged on the downward slope (Papendick et al., 1983). Unlike the older vertical mulch concept, the straw in the slot is left well exposed at the surface (Saxton et al., 1981). Keeping sorghum stubbles as slot mulch and protruding 10 cm above ground level, increased available water by 40 to 50 mm and improved grain yields by 40 to 50% in normal years, and by as much as 400 to 500% over unmulched plots in below-normal rainfall years in a Vertisol in India (Venkateswarlu, 1987).

Unger (1983) lists the following disadvantages of vertical mulching: the residues grown in place may be insufficient; it is difficult to maintain the slots open to the surface; intensive management is required, and it may be costly.

Basin listing

Basin listing (also known as basin tillage, furrow diking, tie-ridging), consists of forming cross-dikes within the main ridges, at distances of 2 m or more. The dikes prevent run-off of water during heavy rains and thereby improve infiltration and reduce erosion (Fig. 14.10).

Basin listing was first introduced into the Southern Great Plains in the 1930's, but was subsequently abandoned because of the technical difficulties encountered. Slow operating speed, poor weed control and cultivation problems, are apparently the main reasons for abandoning the practice in the USA in the 1950's (Hari Krishna, 1989).

Modern technology makes it possible to overcome these problems (Clark and Hudspeth, 1976). Special devices have been developed to block the furrows, others to remove them, if necessary. An attachment for cross-tying can be fitted to the ridger, which is quickly dropped at the desired intervals during ridging (Tschiersch, 1978).

Weed control is entirely by herbicides, eliminating the difficulties of cultivating the

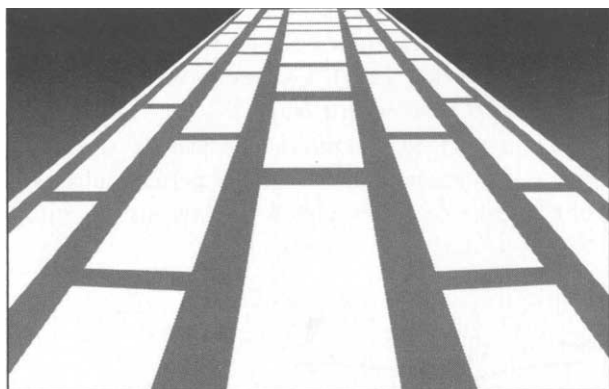


Fig. 14.10. Water conservation with tied ridges. The dikes prevent run-off and improve infiltration. Not suitable for low-permeable soils and high-intensity rainfall (see Fig. 14.11).

blocked furrows. Larger furrows increase water storage capacity and reduce dam overtopping and subsequent erosion.

Clark and Jones (1981) report average grain sorghum yield increases in Texas of 16% during a five-year period, for blocked furrows, when compared with open furrows. Furrow diking retained run-off and increased cotton lint yields by 15%, also in Texas (Bilbro and Hudspeth, 1977).

Crop response to diking varies considerably from year to year and between locations, and depends on the nature of the soil and on climate-related factors (Hari Krishna, 1989). As expected, tie-ridging is most effective under conditions of limited rainfall and permeable soils.

The system can only prove effective on soils with a sufficiently low infiltration rate to enable ponding of water between the ties, whilst being high enough to prevent waterlogging.

A similar system was used in northern Nigeria; it increased cotton yields significantly by conserving and storing water from the early rains; as a result, the cotton plants were better able to survive the dry period which usually occurs after the early rains (De Wilde and McLoughlin, 1967).

Tie-ridging was tested by ICRISAT for several years under conditions of high-intensity rainfall and found to be unsuitable. In Nigeria, under similar conditions tie-



Fig. 14.11. Ponding of water and breakdown of the dykes in a heavy, impermeable soil. Photo Soil Conservation Service, Israel.

ridging increased waterlogging, development of anaerobic conditions in the root zone, excessive fertilizer leaching, and water table rise in lower slope areas (Kowal, 1970).

Krantz (1981) reports that it was also very difficult to maintain the ties between the ridges and concludes that the technique was not very useful under high-rainfall conditions (Fig. 14.11). He suggests that an alternative approach, which consists in orienting the furrows at a low grade (around 0.5%) was to be preferred; a high percentage of infiltration of low-intensity rainfall is achieved, and the necessary crop drainage during periods of prolonged rains is ensured.

Tie-ridging is recommended primarily for marginal rainfall areas; it requires occasional maintenance during the rainy season (S.A. El-Swaify et al., 1984). In heavy clay soils, listing in alternate furrows may be desirable to avoid oversaturation during heavy rains; keeping wheel rows undiked can also facilitate field operations (Krishna and Gerik, 1988). The major disadvantages of the system are the need for special equipment for building and removing blocks, and that severe rainstorms may cause washouts by overtopping (Unger, 1983).

Overall, it is possible to conclude from the foregoing that tie-ridging is a low-cost technique, that can result in significant benefits to semi-arid agriculture, if applied properly on a long-term basis and where rainfall is deficient (Hari Krishna, 1989).

Contour or graded bunding

Contour or graded bunding is used in semi-arid tropical areas of India for decreasing soil erosion and conserving water above the bunds by increasing infiltration in the soil. Whilst well-designed and maintained systems of bunds have been found to decrease soil erosion for the watershed as a whole, substantial erosion and sedimentation occur within the areas between the bunds. Although large amounts of water are held back by the bunds, the stagnant water above the bunds often interferes with field operations and/or results in waterlogging (Krantz, 1981). On small farms, bunds constructed on the contour bisect the small fields, and the bund contour is often adjusted to the farm's boundary. As a result, the bunds are often breached during intense rains (Krantz, 1981).

Minimal tillage

Justification

Research in recent years has repeatedly shown that frequent tillage operations are rarely beneficial, and frequently detrimental, in addition to being costly and wasteful of energy.

The problems are most acute under conditions of intensive cropping, involving frequent tillage operations and much movement of machinery – especially on soils with a relatively low organic-matter content (Free, 1960).

A worldwide tendency to reduce tillage operations to a minimum has been in

evidence in recent years. This involves two complementary approaches: to omit any tillage operation whose cost exceeds its contributions to increased productivity or efficiency of production, and to combine agricultural operations.

Definition

'Minimal tillage' can be defined as a method aimed at reducing tillage to the minimum necessary for ensuring a good seedbed, rapid germination, a satisfactory stand, and favourable growing conditions.

Minimal tillage substitutes herbicides for mechanical weed control during part of the fallow season, with tillage performed later to loosen the soil and prepare a seedbed (Jones et al., 1990).

In the Central Great Plains, for example, contact or pre-emergence herbicides are applied shortly after wheat harvesting to kill all weeds rapidly and to inhibit the germination of weeds or volunteer wheat until late in the following spring. One sweep tillage, and one or two rod weeding are required until sowing in early September. Fallow efficiencies vary from 33 to 38% (Greb, 1983).

Advantages and problems

The major advantage of combining chemical weed control with tillage is that most residues are maintained on the surface during the fallow period, thereby providing protection against soil erosion, improving infiltration and conserving water (Papendick and Miller, 1977).

Minimum tillage has been made practical and economical by the development of special equipment for combined tillage and sowing operations, and by the enormous progress achieved in chemical weed control, both selective and general, which has rendered superfluous many previously indispensable tillage operations. Minimum tillage frequently gives yields as good as, or even better than, the conventional methods; the advantage in yield of maize obtained with minimum tillage was found to be even greater in years of low rainfall than in years of heavy rainfall (Van Doren and Ryder, 1962). These favourable results are ascribed to improved soil physical conditions, including higher rate of infiltration, less soil resistance to penetration, and less soil compaction, or to indirect effects, including fewer weeds, more root growth, better vegetative development, and less lodging (Rao et al., 1960).

These advantages were more apparent on coarse and medium-textured soils than on the more heavy clay soils. In general, it takes from two to three years before the favourable effects of minimum tillage are fully apparent. The improvement of soil compaction, due to previous conventional tillage methods, is a gradual process.

In general, germination is less even with minimum tillage than with conventional tillage. Moreover it should be noted that there is more danger of failures in crop establishment if the soil is worked when too dry than when it is too wet.

Minimal tillage may entail certain changes in crop management: for example, conventional tillage, by promoting aeration, increases the rate of decomposition of

organic matter in the soil, and hence the release of nitrogen to crop plants. Under conditions of minimum tillage, it may be necessary to offset the reduced supply of nitrogen from the soil reserves, by increased mineral fertilization.

Certain problems related to the use of minimum tillage have not yet been resolved. Herbicide costs are still frequently in excess of tillage costs. Too little is known of the long-term effects of herbicide residues in the soil. The possibility that herbicide-resistant strains of weeds may develop has also to be considered.

Baemer and Bakermans (1973), in a review of minimum-tillage systems, conclude that the data for maize production indicated greatly reduced erosion, reduction in run-off, and no decrease in yield compared to conventional tillage. By 1974, over eight million ha were under this system (USDA, 1975).

Zonal tillage

Studies of soil structure in the root zone of maize have shown that optimum conditions in the row are different from what is optimum between rows. From this it was concluded that fields in which row crops are grown should be managed as two distinct zones, called by Shear (1965) 'seedbed zone and rootbed zone', and by Larson (1962) 'seedling environment zone and water management zone', respectively. Zonal tillage is therefore an adaptation of minimal tillage to row crops (Fig. 14.12).

The importance of keeping compaction confined to a particular zone will depend on a number of factors (Srivastava et al., 1988):

- susceptibility of the soil to puddling and compaction;
- value of energy saving and water conservation through zonal soil management;
- negative effects of compacted zones on neighbouring cropping zones.

As tillage requirements are not the same for all crops or soils, a number of different approaches have been developed, to achieve the aims of zonal tillage.

In some till-plant systems, a bed splitter is used after harvest, so that the positions of the planted row and the interrow area are alternated each year (Unger, 1984).

Moldboard plough wheel-track planting

In this method, only a single trip over the field is required. The tractor pulls a plough and a planter, simultaneously. The seed row is centred either in the tractor or planter



Fig. 14.12. Zonal tillage.

wheel tracks. Experience has shown that the tractor (or planter) wheels make a firm, satisfactory seedbed even on cloddy soil, ensuring rapid and even germination.

The soil between the rows remains rough and loose, and is therefore better able to absorb moisture and to reduce run-off. Weed seeds lie dormant in the loose soil, until rain falls or the field is irrigated.

Wheel-track planting was found to save about 40% of tillage costs (Peterson et al., 1958). By adding two extra rear wheels to the tractor, it is possible to use a four row planter. Experience has shown that the optimal soil moisture for ploughing is also optimal for seed germination (Hansen et al., 1958). Any delay between ploughing and sowing always reduces soil moisture, which may become too low for seed germination. In order to prevent the top soil from drying out and becoming hard before sowing, it is essential to plough and plant the field on one and the same day.

Though plough-planting involves clean tillage, it can contribute to soil conservation, because ploughing is delayed until shortly before sowing. Consequently the soil remains covered by residues for the major part of the erosion-prone period (Griffith et al., 1977).

Till-planting

Several types of till-planting systems have been developed that prepare a seedbed and sow in one operation. Jones et al. (1990) describe a procedure developed in Nebraska, as the most successful system: it involves planting on ridges formed during cultivation of the previous sorghum or maize crop. A wide sweep with trash guards, preceded by a coulter, is operated ahead of the planter opener at a depth of 5 to 8 cm to move residue aside onto the ridge, leaving a trash-free zone for planting. Pre-emergence herbicides are often banded over the planted row.

Ridge cultivation

The frequent traffic of machinery and equipment, especially in irrigated fields, causes a breakdown of soil structure in the top soil layer, and considerable compaction of the lower layers. As a result, it is difficult to prepare a good seedbed, germination is adversely affected, and irregular stands are obtained.

One of the methods developed to overcome these drawbacks is 'ridge cultivation'. The principle of the method is to establish permanent 'tracks' in the field along which the tractors travel during the entire period of soil preparation and inter-row cultivation, and to create a deep-tillage zone between the tracks, which will then serve as the seedbed and growing area for the crop.

It has been shown that the first time the tractor crosses a ploughed field, the soil is packed ten times as much as by subsequent passages (R.L. Cook et al., 1958). Much compaction of the soil can therefore be avoided by driving along old tracks.

Ridge cultivation was originally developed for preparing seedbeds in fields that were to be irrigated by furrow irrigation; it was soon found, however, that the method has merits which are quite independent of the irrigation system adopted. The

furrows between the ridges provided efficient drainage during the rainy periods; in early spring the ridges dried more rapidly, and the soil warmed up sooner, than in land cultivated 'on the flat', in the conventional manner.

All the unfavourable effects of compaction following tillage operations remained confined to the furrows between the ridges; as a result, only one-quarter, approximately, of the field was adversely affected, whilst roots found favourable conditions in the remaining three-quarters, in which soil structure was well preserved and ensured favourable conditions of aeration and moisture.

There are four stages at which ridge cultivation can be initiated:

- (1) immediately after harvesting the previous crop;
- (2) when preparing the land, before winter;
- (3) during winter cultivation;
- (4) in spring, for seedbed preparation.

Precision tilling

If it is decided to start with ridge cultivation immediately after harvesting the preceding crop, the method used had been called 'precision tillage' (Fig. 14.13).

In this case, the first operation consists of chopping up the residues of the previous crop. Then follows use of a tool consisting of two 75-cm shanks equipped with chisels, followed by three bed-listers, all mounted on a cultivator frame. In a single

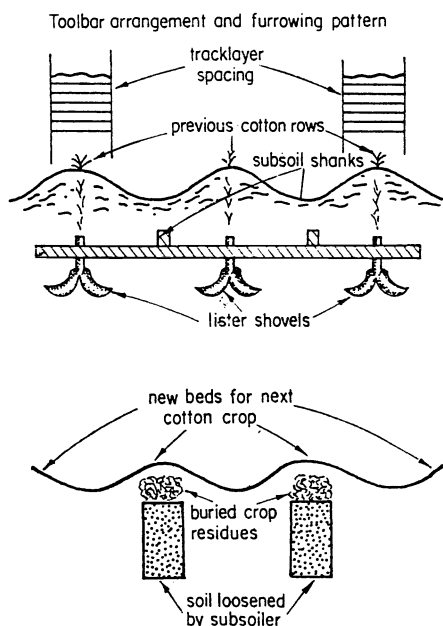


Fig. 14.13. Schematic presentation of precision tillage. From Johnson (1963). By permission of World Farming.

operation, the soil is sub-tilled to a depth of 50–65 cm by the chisels, whilst the listers place the ridges accurately above the zone loosened by the chisels, effectively covering the residues of the previous crop.

During the winter months, the ridges are reshaped and weeds are killed by a special implement called a disk-bed shaper, the wheels of the tractor always travelling in the furrows. If the field is too wet for cultivation, weeds are controlled by spraying.

Ridge cultivation also has beneficial sanitary effects. By keeping the top soil dry, while roots can draw on the water underlying the ridges and in the furrows, it is an accepted means of controlling soil-borne diseases such as *Rhizoctonia solani*, *Sclerotium rolfsii* and others (Palti, 1981). However, if irrigation water is relatively saline, ridging may cause salts to accumulate, and favour pathogens, such as *Macrophomina phaseoli*, that take advantage of plants growing under stress.

Various systems of zonal tillage have been developed for Vertisols in India (S.A. El-Swaify et al., 1984), and for red-brown soils in Australia (Adem and Tisdall, 1984). These systems are designed around permanent beds and consequently provide excellent control of machine operations. Contour banks or furrows, vertical mulching, tie ridging, etc., could be incorporated (Yule, 1987).

In India, results from experiments carried out by ICRISAT have shown that for Alfisols, whose subsurface layers are richer in finer particles, ridging exposes layers in the furrows that have low permeability and are more prone to erosion and have a high run-off potential. Mixing the finer particles with the sandy top soil in the ridge or bed, as usually happens with inversion tillage, increases the run-off in the ridge or bed.

Broadbed-and-furrow system

The broadbed-and-furrow system developed by ICRISAT for the semi-arid tropics was found to be the most successful system for facilitating cultivation and to control excess water (Fig. 4.11). The broadbed is 100 cm wide and the furrows about 50 cm. Two, three or four rows are planted on each bed. The system can be easily prepared and maintained with animal power or light tractors. The excess water is led off the land at a controlled velocity by many furrows, so that erosion and run-off are relatively low. The water discharges into grass waterways which lead to a reservoir (a dug tank or small dam). The optimum slopes for the bed-and-furrow system are 0.3–0.6% on Alfisols (red soils) and 0.4–0.8% on Vertisols (black cotton soils).

Experience in India has shown that the graded broadbed-and-furrow system has the following advantages: it can be laid out on a permanent basis, facilitates land preparation during the dry, non-crop season, reduces soil erosion, provides surface drainage, reduces compaction in the plant zone, and reduces the power and time required for agricultural operations (Krantz, 1981).

On soils lacking stability, broadbed-and-furrow systems will break down and do more harm than good as run-off and erosion control measures (S.A. El-Swaify et al.,

1984). On Alfisols, watersheds designed with this system generated significantly more run-off and soil loss than alternate designs with flat systems (Pathak et al., 1983).

No-tillage

Description

No-tillage (also called zero tillage, slot planting, ecofallow, sod planting, chemical fallow, direct drilling) relies completely on herbicides, both contact and pre-emergence, for weed control throughout the fallow season (Greb, 1983).

No-tillage requires no seedbed preparation other than opening a slot for seed placement, usually with a coulter operated in front of a seeder equipped with disk or chisel openers (Mannering and Fenster, 1983).

No-tillage was originally developed for orchards and pasture renovation. As more effective herbicides became available, no-tillage was adapted to large-scale field crop production (Unger, 1982), and special systems were developed for subhumid and semi-arid regions in temperate and tropical climates (Lal, 1986a,b).

Importance

Unger (1983) writes that “no-tillage is probably the foremost crop management practice developed in recent years, which decreases labour, energy, and equipment needs”. Though results from no-tillage were still limited at the time of writing the above, Unger believed that “the systems have potential for becoming the prime production method wherever crops are grown”.

Since the early 1980's, no-tillage has become a widely accepted conservation practice. In the USA alone, no-tillage farming was used on approximately 3.3 million ha by the early 1980's (Lessiter, 1982).

Advantages

Because weeds are controlled chemically, all crop residues remain on the soil surface, thereby improving water infiltration, reducing water losses by evaporation and reducing erosion.

When water was applied with a rainfall simulator to a Mollisol, at Bushland, Texas, soil loss with stubble mulch tillage was 6.56 t/ha, but only 2.15 with no-tillage (Unger, 1978).

When sufficient residues were present (>2500 kg/ha), Unger (1984) reported greater water storage and higher sorghum grain yields with no tillage than with other treatments on the same Mollisol at Bushland.

In Western Nigeria, Lal (1976) also found a higher water-holding capacity in no-tillage plots than in clean-tilled plots; these results he attributed to differences in organic-matter content and texture of the surface horizon.

In semi-arid areas, much of the water from precipitations of 15 mm or less, is lost by evaporation. Because the depth of penetration of the rainfall is less in the more

porous ploughed soil, the potential for loss through evaporation is greater than in a no-tilled soil. This is one reason for the more favourable moisture régime usually found in no-tilled soils (Power and Doran, 1988).

No-tillage is also highly effective in controlling wind erosion, as shown by the following data from an experiment carried out on a sandy soil in Ohio in which soil loss from clean, fall-ploughed land, was 26 t/ha as compared to only 1.2 t/ha for no-tilled land protected by a residue cover of 5.6 t/ha (Woodruff, 1972).

Leguminous crops can be grown as cover crops to provide mulches in no-tillage systems. Hairy vetch or crimson clover, sown in the fall, and killed by herbicide application in spring prior to sowing maize, not only provided a mulch cover, but also the equivalent of 112 kg N/ha (Mitchell and Teel, 1977).

A no-tillage system for high-clay soils

Soils with a high content of montmorillonitic clay, such as Vertisols, present unique problems of soil and crop management due to low infiltration rates and high water-holding capacities, resulting in poor drainage. Tillage of a dry soil requires high energy inputs. The range of water content enabling tillage without causing damage to soil tilth is very narrow; primary tillage, when the soil at cultivation depth exceeds this range, causes soil compaction, and subsequently produces large clods, which require frequent tillage and extended weathering before an adequate seedbed can be produced. Traffic on wet soil leads to puddling and compaction.

Morrison et al. (1988) have developed a technology for high-clay soils that aims at overcoming these problems by combining elements of no-tillage, mulch farming, precision tillage and improved management practices.

The components of the system are:

- no-tillage;
- crop residues on soil surface;
- raised wide beds, to provide well drained cropping zones (cf. p. 712) which will not be compacted by wheel traffic;
- controlled traffic;
- crop sequences that provide crop residues, and management flexibility;
- fertilizer placement to optimize fertilizer efficiency; and
- equipment adapted to the system.

Limitations of no-tillage

In the high-precipitation zone in the Northwest Pacific, problems have been encountered with direct drilling into heavy cereal stubble: high crown set, phytotoxicity to seedlings from surface residues, fertility imbalance, increased disease incidence, increased weed infestation, and, in some cases, a lower soil temperature in spring. All these have resulted in yields that are often 10–30% lower than with conventional tillage (Papendick et al., 1983).

Soils that are unsuitable for no-tillage are heavy clays, with low infiltration; soils susceptible to crusting and compaction, that have poor internal drainage, and/or low biological activity (Lal, 1986a,b). However, procedures for overcoming some of these problems have been developed (see the preceding section).

Degraded soils, with less than 20% clay, which do not have marked shrink–swell characteristics, are not suitable for no-till farming, unless their soil structure is improved by the addition of organic matter.

Soils in the semi-arid tropics, such as Alfisols, that undergo severe hardening during the dry season, require primary tillage to enable rain infiltration and root penetration, and are therefore not suitable for no-till (H.V. El-Swaify et al., 1985).

In a study of net returns from no-till as compared to conventional tillage, Featherstone et al. (1991) found that under favourable moisture conditions yields and net profit were lower for no-till; as stress increased the performance of no-till improved relative to conventional tillage, and at high moisture stress, average yields and net returns were higher than those on conventional tillage (Fig. 14.14).

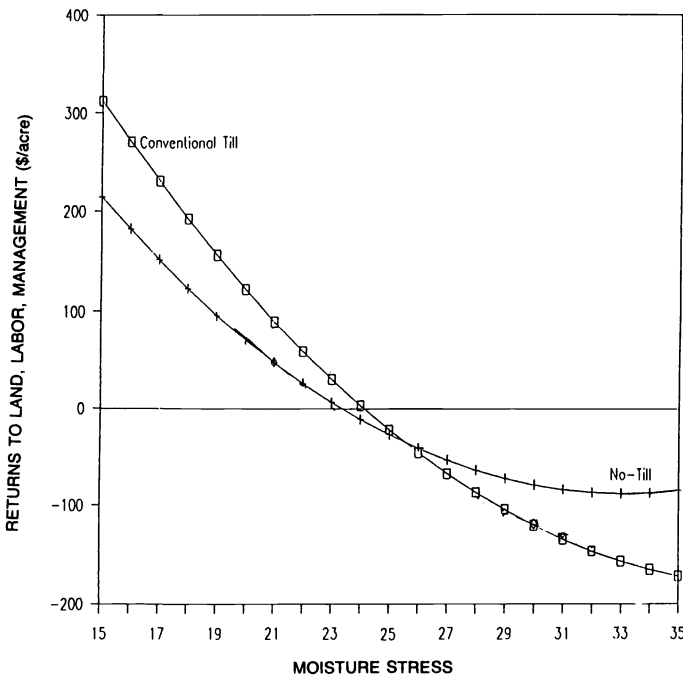


Fig. 14.14. Comparison of profit as a function of yield of different tillage systems under different soil moisture régimes. From Featherstone et al. (1991). By permission of the American Society of Agronomy, Inc., the Crop Science Society of America, Inc. and the Soil Science Society of America, Inc.

Summary

It has been shown in this chapter that most tillage operations have both beneficial and detrimental effects.

Ploughing, the traditional and most basic tillage operation in temperate climates, inverts the soil, covers manure and crop residues, and destroys weeds, many insects, and disease agents. Frequent ploughing, however, creates a plough sole which impedes infiltration and root penetration; the very 'cleanness' achieved is, in the dry regions, a factor for increased soil loss with disastrous results.

Subsoiling improves infiltration, reduces erosion, and breaks up hardpans; it may, however, favour the spread of diseases carried from one crop to the next on the crop residues or stubble, as well as encourage the development of perennial weeds.

Too frequent tillage of dry soils causes a breakdown of soil aggregates, resulting in poor soil structure, crusted soil surfaces, and reduced resistance to erosion.

Tillage of *wet soils* causes excessive compaction, resulting in poor infiltration and decreased aeration of the soil.

Deep ploughing is very effective in the destruction of perennial weeds, and in ensuring a complete drying of the soil. The latter is an important factor in achieving improved soil structure and sanitation of soils in arid areas, particularly in those that are under irrigation. Deep ploughing is, however, extremely expensive; it leaves an uneven soil surface requiring renewed levelling, and may reduce soil fertility by inverting the most fertile layer and replacing it with biologically inactive soil.

From the foregoing, two essential conclusions can be drawn:

(1) Tillage operations should be reduced to the absolute minimum required for achieving the farmer's purpose.

(2) By alternating different methods of tillage, and applying each method under the conditions in which its beneficial effect is maximized, it is possible to reduce the detrimental effects of tillage to a bare minimum. A 'rotation' of tillage operations may therefore be as important as a rotation of crops, and the two are best integrated.

Dryland systems in which crop residues are removed or burned, ultimately lead to severe soil deterioration and loss of fertility. Various methods of conservation tillage have been developed, all of which are based on stubble mulching, i.e. retaining crop residues on the soil surface. Experience has shown that for dryland agriculture, conservation tillage is the most effective means to protect the soil from erosion and improve the moisture régime of the soil.

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CHAPTER 15

Plant Population and Planting Geometries

Reducing plant density under dry conditions in order to achieve a balance between the amount of plant cover and a limited soil moisture, has long been an accepted cultural technique. In rainfed agriculture “plant population is one of the major management variables available to the farmer” (Gardner and Gardner, 1983). The optimum population depends on the characteristics of the plant and the amount and distribution of the rainfall (*ibid.*).

It is only in the 1950's that agronomists became fully aware that the higher potential yields made possible by the favourable water régimes provided by irrigation, the high soil-fertility levels resulting from heavy applications of fertilizers, and the genetic potentials of new varieties and hybrids, could be achieved only after appropriate adjustments of the plant population. Research on adjusting population levels to all other factors of production therefore became very extensive at the time.

General plant-density–yield relationships

Total dry-matter production (biological yield)

When plants are widely spaced, dry-matter yields will at first tend to increase linearly with increases in plant density. This indicates that no appreciable competition is occurring between neighbouring plants. Further increases in density bring diminishing returns, indicating that competition between plants is making itself felt, and that the production of the individual plant is being reduced; this reduction is, however, still being more than compensated for by the increase in the number of plants.

A further increase in density results in a ‘plateau’ of practically constant yield of dry matter, indicating that an equilibrium has been reached at which the increase in production due to increased plant numbers compensates almost exactly for the reduction in the production of the individual plant.

To obtain the maximum yield possible, it is essential for the crop to utilize as

efficiently as possible all available production factors: water, nutrients, light and CO_2 .

The number of plants required per unit area to achieve this aim will depend on the nature of the crop and on its environment. This number cannot be too small, or not all the production potential will be fully utilized: nor can it be too large, or excessive plant competition will reduce the overall efficiency of the crop.

Increasing the number of plants per unit area, reduces the volume of air and soil that the individual plant can exploit, and therefore increases competition between plants for soil nutrients, moisture, CO_2 and light. Competition for physical space, however, is rarely limiting (Black, 1966), though such competition among roots may occasionally occur when they have to penetrate dense layers or hard clods through which there are relatively few channels (Donald, 1963).

Maximum exploitation of the factors needed for growth is achieved only when the plant population exercises maximum pressure on all the above factors (Donald, 1963). As a result, the individual plants are under relatively severe stress because of inter-plant competition. In subterranean clover, for example, the total dry matter produced per plant at a wide spacing (6 plants/m²) was 34 g, whilst at the density which produced maximum yields (1500 plants/m²) the individual plant produced only 0.6 g, or less than 2% of the former amount (Donald, 1954). Thus we come to the somewhat paradoxical conclusion that maximum yields are obtained from plant populations which do not allow the individual plants to achieve their maximum potential.

Economic yield

Many studies have shown that the relationship of yield of seed or fruit (economic yield) to density is different from that of total dry-matter production (biological yield). In the latter, total production yields rise with increasing density to a maximum, which then remains practically constant (Donald, 1963). At this density, any increase in total dry-matter yield per unit area due to an additional number of plants, is offset by an equal loss due to the decrease in weight per plant. This relationship also applies to other vegetative yields, such as total yield of potato tubers (Holliday, 1960).

The relationship of seed production to population density is different. As plant density increases, the yield of seed increases to a maximum, which remains constant within a certain range, and then declines more or less steeply as population pressures increase still further – even when moisture and nutrients are not limiting (Holliday, 1960). With maize, for example, the decline in yields is fairly steep when the optimum density is exceeded, whilst with cotton – a crop in which individual plants have a far greater ability to adjust to population density – the graph depicting yield of cotton-seed exhibits a fairly wide plateau of optimum densities (Fig. 15.1).

Donald (1963) points out that the two curves of seed yield and biological yield are

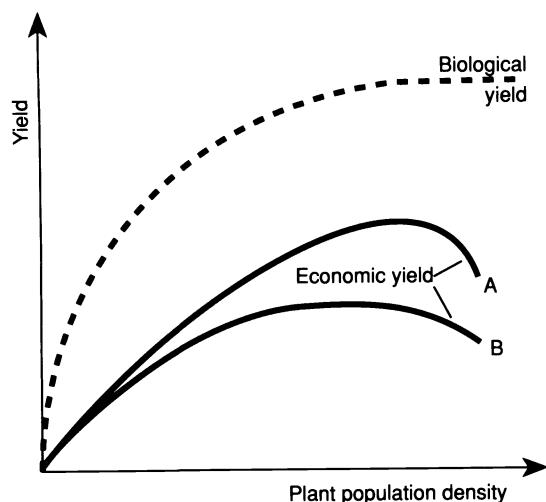


Fig. 15.1. Generalized curves showing effect of plant population on biological yield and economic yield. A: maize (grain). B: cotton (seed).

interdependent, and that peak seed yields occur approximately at the same density at which the biological yield starts levelling off. He therefore suggests that “the minimum density giving the ceiling biological yield may also be the density giving the maximum seed yield”.

In the young plant, most of the net assimilates are used for the production of additional leaves. With the appearance of the inflorescence, competition for assimilates between the leaves and the inflorescence takes place. Then, when seed formation starts, most of the assimilates move to the grain.

Thus there exists an internal competition, within the individual plant, between vegetative and reproductive parts. This internal competition becomes more severe as competition between plants increases, i.e., with increasing plant population pressures.

As plant density is increased, changes may occur in the allocation of assimilates to different parts of the plant, as a result of which a greater proportion of the plants (or of the reproductive parts of a individual plant), may become barren. Grain production then shows a decline in yields, whereas the total dry-matter production may remain constant (Harper, 1961).

In maize, it has been demonstrated that the reduction in grain yield resulting from excessive plant density is due primarily to the increase in the percentage of barren plants (Prine, 1966). It was found that if the stand was thinned shortly before silking, the average number of ears per plant was the same as in a widely spaced stand. When thinning was done during the ten days after the first plant had silked, the number of ears was markedly reduced in comparison with widely spaced plants. Making more

light available after silking had no effect. In maize therefore, there is a critical period for light in relation to grain formation; stressed plants aborted their ears from three days before silking until about eight days after the emergence of the silk.

As a result of the differential effect of competition on biological and economic yield, the amount of stover (maize straw) required to produce a kilogram of grain decreases with increasing plant density up to a certain level; a further increase in density beyond this level then results in a lower grain/stover ratio (Dungan et al., 1958).

Components of yield

As planting density increases, most components of yield of the individual plant are reduced. However, there are cases in which certain components do not follow this downward trend. For example, in subterranean clover it was found that, while the number of inflorescences per plant and the number of seeds per plant decreased progressively with increasing density, the number of seeds *per inflorescence* and the weight per seed rose to a peak value as density increased, up to a certain critical level, and fell only beyond this level of density. This was, incidentally, the level that corresponded to maximum seed yield per unit area (Donald, 1954).

Donald (1963) suggests the following explanation: at wide spacings there is little competition between plants at the early stages of growth, and a large number of primordia are initiated in early plant growth. As growth proceeds, inter-plant competition increases progressively. The load of inflorescences reduces the number of seeds per inflorescence and reduces seed weight, compared with somewhat denser stands. In moderately dense stands, inter-plant competition may be sufficiently severe at the time of flower initiation to reduce the number of floral primordia to a level at which the load on the individual plant is not excessive and maximum efficiency in seed production, as expressed by seed number and size, is achieved.

In very dense stands, both inter-plant and intra-plant competition are sufficiently severe to reduce all components of yield.

An interesting feature is that among the several highly plastic components of plant yield, the weight of the individual seed is only rarely influenced by changes in plant density. Harper (1961) considers this to be an internal or physiological homeostasis with respect to the organ that is essential for reproduction and dispersal. However, as we have already seen, there may be very considerable differences in the manner in which different crops react to plant density in other connections (*ibid.*).

Crops with *indeterminate growth* systems, such as *Vicia faba*, “in which the flowering apices do not arise directly from the major vegetative apices”, respond to density mainly by changes in the *number* of parts formed. On the other hand, crops with *determinate growth*, such as sunflowers, respond mainly by changes in the *size* of the parts.

Crops in which a determinate phase follows an indeterminate phase (after vernali-

zation and photoperiodic response), such as winter wheat, may respond by changes in the number of parts during the indeterminate phase, and by changes in the size of parts during the determinate phase.

Interrelationships between plant density and factors affecting production

Light

Water régime and nutrient supply to the crop can be regulated to enable the maximum number of plants to achieve their full yielding potential; however, increasing the number of plants per unit area will reduce the amount of light available to the individual plant, due to greater shading.

With irrigation and modern cultural practices, light is most frequently the factor limiting productivity, so that yields ultimately depend on the efficiency with which light is intercepted by the crop.

There is a basic difference in competition between plants for light and for other factors needed for growth. Moisture, nutrients, and CO₂ are withdrawn by the plants from a common pool. In plant populations of a single crop, assuming that differences in competitive ability between individuals of a similar genotype are not very great, the plants will share equally in the supply, until it is exhausted. By contrast, there is no pool of light that becomes exhausted as a result of withdrawal by the plant community (Donald, 1963).

A sparse stand, by withdrawing less water from the common pool at an early stage of growth, may 'save' water that will be available to the crop at a later, more sensitive stage. Any available light that is not intercepted by the canopy at a given moment, is lost to the crop. "Light energy is instantaneously available and it must be instantaneously intercepted" (Donald, 1963).

Competition for light is universal and is absent only for a short period after emergence, or in the very wide spacings that are characteristic of plant communities which have become adjusted to arid conditions. In these last, the leaf cover never reaches a density which ensures the most effective utilization of radiation (Blackman and Black, 1959). In contrast with competition for water or nutrients, which increases in severity with decreasing availability, competition for light in a dense population will be equally acute under conditions of high light intensity and of overcast skies (Donald, 1963). Competition between plants is not a static process, and the intensity of competition will depend on the time when it occurs. In the early growth stages, there will be little mutual shading and even at relatively low light intensities the plant will be able to photosynthesize with full efficiency.

As the plants develop, mutual shading increases, and light begins to become a limiting factor. When plants reach the flowering stage, they may even lose weight on cloudy days (Jackson, 1963).

Competition for light may be between plants, when one casts a shadow over any other, or within a plant, when one leaf shades another.

Essentially, there are two basic ways of ensuring maximum interception of light by the canopy: by improving the foliage pattern, and by increasing plant density.

(a) *Improving the foliage pattern.* The most efficient plant canopy is not that with the most leaves, but that in which the inter-plant and intra-plant competition for light is reduced to a minimum, so that the canopy as a whole intercepts a maximum of light. This aspect has been treated in detail in Ch. 7.

(b) *Increasing plant density.* The light intensity required to give a maximum rate of photosynthesis by the individual leaf is about 1500–2000 fc, whilst light intensities in the field may reach 10 000 fc (Donald, 1963). For example, in a sward of bermuda grass (*Cynodon dactylon*), isolated leaves were light-saturated at 2500–3000 fc, whilst the light required to saturate the sward as a whole ranged up to 7000 fc, depending on height and foliage pattern (Alexander and McCloud, 1962).

It is therefore possible to reduce the distance between individual plants, so as to increase the efficiency of the plant canopy *as a whole* in utilizing the available sunlight. However, there is an optimal ratio of leaf area to ground surface (LAI) beyond which increasing plant density will increase excessively the proportion of the foliage which is below the compensation point.

An interesting experiment by Miller (1956) illustrates why, up to a certain plant density, the reduction in production of the individual plant is more than compensated for by the increase in the number of plants (Fig. 15.2). A reduction of up to 40% of the total sunlight causes a reduction of only 14% of the yield of the individual maize plant; however, further reductions in sunlight cause a steep decline in yield.

De Wit (1960) has shown that there is a linear relation between the reciprocal of yield and the area available per plant. The slope of this line decreases with increasing

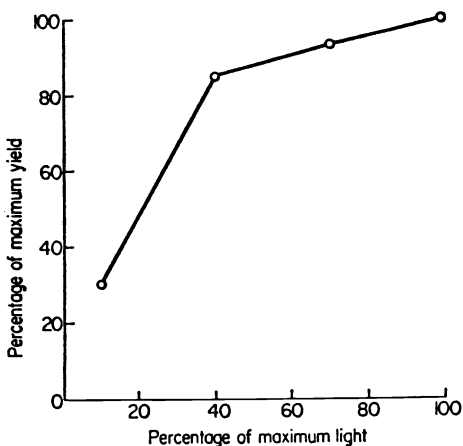


Fig. 15.2. Grain yield of maize in relation to light. Based on data from Miller (1956).

yield when the potential for yield is high. This could be expected, for a single plant will be able to cover more area the more its growth is promoted by favourable growing conditions.

Moisture supply

Although it is well known that the optimum density for a crop has to be lower than normal under conditions of a limited water supply, the obverse – namely, that plant populations must be increased in order to exploit fully the favourable conditions provided by irrigation – has frequently been overlooked.

Nutrients

All available evidence indicates that, at higher levels of nutrient supply, more plants per unit area are required to exploit fully the higher soil fertility potential and thereby to produce maximum yields, than is the case at lower levels of supply. Conversely, as plant density increases up to a certain limit, the crop will continue to respond to higher levels of added nutrients.

Competition for nutrients

Bray (1954) distinguished between the '*root sorption zone*' which includes the whole volume of soil within the major part of the root system, and the '*root surface sorption zone*' which relates only to the thin volume of soil adjacent to each root or root hair surface, from which the plant effectively obtains nutrients with limited mobility, such as exchangeable potassium or adsorbed phosphorus.

Bray postulated that competition between neighbouring plants for water and nutrients occurs in three stages, which he called the 'plant competition sequence'. When the plants are so far apart that none of their root sorption zones overlap, no competition for water and nutrients occurs. When the root sorption zones of neighbouring plants interpenetrate, competition for the relatively mobile nutrients occurs. It is only when the root surface sorption zones interpenetrate, that competition for the nutrients with limited mobility takes place. Therefore, depending on plant density, there may be no competition for nutrients between neighbouring plants, competition for mobile nutrients only, or competition for both relatively mobile nutrients and those with limited mobility.

As plant density increases, with resultant yield increases, competition for the relatively mobile nutrients is intensified. Amounts that would have been adequate for lower plant population densities become deficient and limiting, so that soil nutrient requirements increase. For the relatively immobile nutrients, such as exchangeable K, the increased competition results in more efficient uptake and the soil nutrient

requirement will increase more slowly with increases in plant density than is the case for the more mobile nutrients.

In a study on maize concerning the relationship between density of population and different levels of nitrogen supply, it was found that the higher the level of nitrogen was, the greater would be the plant population required for achieving maximum yields (Fig. 15.3). With a low supply of nitrogen the maximum yield of grain was 4720 kg/ha, which was obtained with a population of 3 plants/m²; with a medium nitrogen level, the maximum yield was 5800 kg/ha, obtained with 4 plants/m²; with a high nitrogen level, the highest yield was 7430 kg/ha which required a density of 5 plants/m² (Lang et al., 1956). At low levels of nutrient supply, dense populations may have specific adverse effects on crop plants. In spacing experiments with rye-grass (*Lolium rigidum*) in Australia, it was found that when the nitrogen supply was limited, the nitrogen content of the grass fell from 1.8% for widely spaced plants to 1%

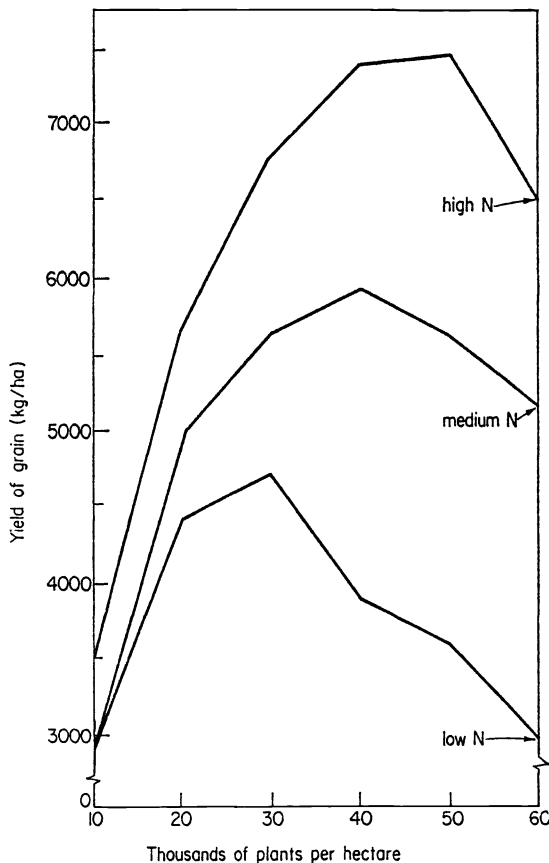


Fig. 15.3. Effect of plant population at various nitrogen levels on grain yield of maize. From Lang et al. (1956). By permission of the American Society of Agronomy, Inc.

for extremely crowded plants (Donald, 1954). In addition, the *total* nitrogen taken up by the sward was less with crowded plants than with more widely spaced plants. Donald (1963) suggests that the plants submitted to excessively severe competition had a poorer root system and were less efficient in the uptake of nutrients from the soil than were less stressed plants.

Breeding for adaptation to high plant densities

When production is not limited by moisture and nutrient supply, and maximum interception of available light is achieved by an optimum plant population, the only means of increasing productivity further is to use genotypes with a greater adaptation to high plant densities.

Before the advent of selective herbicides, an essential property of the cultivars in general use, was their ability to compete with weeds. There was no difference in this respect, between the low-input varieties of subsistence agriculture, and the improved varieties of modern agriculture. In small-grain cereals, for example, high competitive ability was the result of profuse tillering, tall plants with drooping leaves, a relatively low harvest index (HI), and an extensive root system (Fig. 15.4a). Intra-varietal competition was severe and resulted in a marked drop in yield at moderately high plant population densities. This, in turn, resulted in a relatively low potential yield ceiling, even under the most favourable environmental conditions.

After the use of selective herbicides became commonplace, the ability to compete with weeds became of secondary importance compared with the need for plants with a much higher yield potential than those available at the time. We now know that the type of plant required for this purpose should have limited tillering capacity (for reasons explained in Ch. 8), short, sturdy stalks with a high resistance to lodging, narrow upright leaves, a very large ear, and a high harvest index (Fig. 15.4b). To compensate for the low tillering capacity, plant population densities had to be high in order to make effective use of high-input levels necessary for high yields. The low intra-varietal competitive ability of the individual plants was not a liability in a weed-free environment, but was actually an advantage because it allowed the high population densities required.

The semi-dwarf high-yield varieties of wheat and rice developed at the international institutes in the 1960's, are the embodiment of the plant type described above, and come very near to the ideotype proposed by Donald (1963), with one exception: instead of the unicum he suggested, they have a moderate tillering capacity.

Experience worldwide has shown, that this plant type, in combination with high plant densities, high nutrient levels and favourable moisture régimes, is capable of producing yield levels that are twice as high as those of the older tall-growing varieties with high competitive ability (Fig. 15.5).

In other crops too, besides the small-grain cereals, efforts were being made to



Fig. 15.4. Two basically different crop plant types: (a) left: the traditional cultivar, before the advent of herbicides with high competitive ability; and (b) right: an ideotype with low competitive ability. Adapted from (a) Janssens et al. (1990) and (b) Donald (1968).

develop varieties making full use of improved cultural techniques, and high levels of inputs. In most cases this required increased plant populations. It was observed that not all the crop varieties which had been bred for the standard plant densities formerly employed, responded in the same manner to increased population pressures. Hybrids have been found to require more plants per ha than open-pollinated varieties in order to reach the point of maximum yield per unit area. However, there are also differences in this respect between hybrids, and increasing attention is being given to the selection of hybrids that perform well in dense populations (Stinson and Moss, 1960).

Different maize hybrids were found to respond differently to plant density. The single cross Hy2 $\times$ Oh7 yielded well at high population densities, whilst WF9 $\times$ C103 yielded best at a lower population density (Lang et al., 1956). Similar results were



Fig. 15.5. Field of semi-dwarf wheat, grown with 450 mm rainfall, which produced 5 t/ha grain. Note dense population of erect plants bearing large, heavy ears. Photo Hazera Seed Cooperative.

obtained in Oklahoma, where significant differences in grain yield were recorded among six hybrids in their response to plant density (Rutger and Crowder, 1967).

In comparing the normal Hy2 maize hybrid with a semi-dwarf mutant, it was found that the compact type yielded slightly more at high population densities than did the normal type at any population density tested. Furthermore, hybrids carrying the same dwarfing genes reacted in a similar way to population pressures (Nelson and Ohlrogge, 1957). At low plant densities, some maize hybrids produce several stems and multiple ears; others produce a single stem and one, or at the most two, ears per stem. It was observed that the hybrids with a high tendency to tiller and produce multiple ears, are those that produce the lowest percentage of barren stalks at high densities. Conversely, varieties that are single-stemmed at low densities, show the highest sterility in denser stands (Lang et al., 1956).

The general conclusions to be drawn from breeding work with maize for high performance in thick plantings are that (a) hybrids differ in their capacity to utilize light for grain production; (b) hybrids that are most tolerant to shade are those that are best adapted to dense stands; and (c) the incidence of barren stalks is greater in the intolerant than in the tolerant varieties, when both are grown in shade (Stinson and Moss, 1960). Another hereditary characteristic of significance is the ability of the plant to resist lodging at high plant densities.

Similar differences in tolerance to dense plantings have been observed in various other crops. Rossiter (1959) found that the ranking of strains of subterranean clover was entirely different when they were grown at wide spacings as compared with greater crop density. In widely spaced plants the later varieties produced the highest yields of seeds, whilst the opposite was true for the dense populations. In this case, the main factor limiting yield was soil moisture, which was sufficient for widely spaced plants but became progressively more limiting with later flowering.

Bunch types of peanuts, beans, and peas, grow in an erect manner, and the pods are concentrated in a relatively small area. To produce maximum yields these varieties must accordingly be more closely planted than the runner types with their prostrate growth.

In order to evaluate the potential yielding ability of different varieties, the plant population should be high enough to exert a near-maximum demand on the fertility of the soil (Duncan, 1954).

Other effects of plant densities

Plant height

With increasing density and competition for light, plant height may be markedly increased. For example, the average heights of wheat plants grown in rows spaced 30, 15 and 7.5 cm apart were 63, 75 and 85 cm, respectively, at the age of 16 weeks (Wassermann, 1963).

The effect on height by increasing plant competition may give conflicting results. In soybeans, for example, close spacing causes the lower internodes to elongate, thereby lifting the lower pods off the ground and facilitating mechanical harvesting (Hoggard et al., 1978). On the other hand, lower light intensity may cause flower abortion resulting in less pods to harvest (Dominiquez and Hume, 1978).

Root systems

The extent and distribution pattern of root systems are markedly influenced by plant density. Very widely spaced plants of maize, which were presumably free from competition, developed a circular distribution of the roots, with a radius of about 75 cm. At high densities, the root systems of the individual plants interpenetrated to a high degree. At a 2.5 cm spacing within rows*, portions of as many as 32 overlapping root

* Each experimental plot consisted of a single row; the plots were spaced 250 cm apart, as a safeguard against between-row influence.

systems could be recorded at any one point beneath or near the row of plants, whilst at an 80 cm spacing there were only two overlapping root systems (Haynes and Sayre, 1956).

Lodging

The risk of lodging is markedly increased by high-population levels (Dungan et al., 1958).

Plant composition

Denser plant populations were found to decrease the protein and oil contents of maize hybrids (Lang et al., 1956).

Plant mortality

At very high densities, competition may be so severe among the plants of a population that a proportion of them will die. In wheat, at a density of 1078 plants/m², only 40% of the plants survived to the age of six months (Puckridge, 1962). This 'self-thinning' did not reduce plant density to that giving the highest yield of grain per unit area. Thus, "plant survival had precedence over total seed production per unit area" (Donald, 1963).

Disease incidence

When sorghum seeds were sown more closely in the rows, the more rapid spread of seedling diseases was assumed to be one of the reasons for the relatively smaller number of plants established, as compared with sowing more sparsely (Porter et al., 1960).

There are occasional instances in which very close planting is effective in reducing the incidence of disease – as is the case for rosette disease of peanuts.

Maturity

In maize hybrids, silking was found to be delayed by one day for each additional plant per m² (Lang et al., 1956).

Planting patterns

The following planting patterns might conceivably influence yields: square arrangements, rectangular arrangements, very elongated rectangles (wide row interval with

very small intervals within rows), irregular spacings in the row (pockets or hills within the row), and the direction of the rows.

Square arrangements

It would be reasonable to expect that square arrangements of plants would be more efficient in the utilization of the light, water and nutrients, available to the individual plant, than would be a rectangular arrangement, as square arrangements would reduce to a minimum the competitive effect of neighbouring plants on one another. For wheat, Holliday (1963) has shown that decreasing row widths below the standard 15–20 cm, i.e., reducing rectangularity, generally increases yield slightly, whilst increasing row widths has a depressing effect on yields.

Rectangular arrangements

The question of rectangularity has great practical significance. When an early farmer attached a hollow reed to his primitive plough, through which seed was fed during tillage, rectangular patterns of stand establishment became standard agricultural practice.

This method of sowing had several advantages over broadcast sowing: a considerable saving in seed, a more uniform emergence and more complete stand, and easier weeding and harvesting. The distance of 30 to 40 cm between rows was very convenient, both for hand- and hoe-weeding, and is characteristic of traditional farming to this day. It was only when animal-drawn hoes were introduced for inter-row cultivation that inter-row distances had to be increased to 75–100 cm. This led to a reduction in yield which, however, was not very marked, because of the relatively low yielding potentials. With the improvements in agricultural techniques and the introduction of varieties with high-yield potential, increases in plant population became essential. With increasing density of plant populations, in order to adjust to higher levels of potential yield, it was found in a number of crops that decreasing the larger dimension (inter-row distances) was more beneficial than decreasing the smaller dimension (intra-row distances) in rectangular spatial arrangements (Holliday, 1963). Fortunately, with the advent of selective herbicides, and in particular pre-plant and pre-emergence applications of them, mechanical inter-row cultivation was no longer indispensable and narrower rows became a practical proposition. One of the most recent trends in crop production is a return to the inter-row distances that were characteristic of primitive farming!

However, extremely narrow rows would be necessary to achieve square spatial arrangements with the plant density required for maximum yields of many crops, such as the small-grain cereals. This would entail considerable technical difficulties in most crops.

With wheat and similar crops, sowing machines with very narrow-spaced coulters

cause difficulties during sowing and have a low efficiency due to the choking of the spaces between the coulters with crop residues or moist soil. Mechanical row-planters, for crops such as groundnuts and cotton, cannot work effectively in rows less than 60 cm apart. When furrow irrigation is practised, ridging for irrigation sets a limit of about 70–80 cm to the minimum practicable spacing between rows. Mechanical harvesting of certain crops, such as sugar beets or cotton, also requires substantial inter-row spacings.

Much research has shown that quite considerable variations in planting patterns have relatively little influence on yield per unit area for a wide range of crops (Harper, 1961). With broad beans (*Vicia faba*), at equal numbers of plants per unit area, row spacings of 17, 34 and 51 cm had no influence on yields per ha (Hodgson and Blackman, 1956).

Very elongated rectangles

Extreme rectangularity may be detrimental to yield, but usually some degree of rectangularity may be just as satisfactory as square planting (Holliday, 1963). In general, the plant population has a greater effect on yield than does the spatial arrangement.

Limited moisture supply

Plant spacing and distribution can be adjusted in a way that influences the time when stored moisture is used (Loomis, 1983). “Choosing the optimum plant population and width of row spacing continues to be one of the most difficult challenges for dryland producers” (Stewart and Steiner, 1990). At too high densities, crop yields are reduced because too much of the soil water is used up for vegetative growth early in the season; too low densities do not effectively exploit available moisture.

Recommendations are frequently made that do not differentiate between crops grown on stored moisture (e.g. summer crops in winter-precipitation regions) and those grown during the summer rainfall season.

For crops grown in summer-rainfall areas, the usual recommendation is to increase the distance between plants within the row, to adjust to a low moisture supply. Thus Karper et al. (1931) reported that maximum yields of Milo sorghum were obtained at spacings of 45–90 cm in the row and 90 cm between rows under conditions of limited rainfall.

The dynamics of competition for moisture are evidently different for a rain-fed crop than for a crop growing on stored soil moisture.

For sorghum grown in summer, in a winter-rainfall area, and entirely dependent on stored soil moisture, it was found that the accepted procedure of increasing the distance between the plants within the row, in order to adjust to low moisture levels,

generally defeats its own purpose: the young plants, with little or no intra-row competition, show excessive vegetative development; soil moisture is rapidly depleted, and the plants are unable to form satisfactory ears or to mature their grain normally. The alternative is to space plants more closely within the row, and to increase the distance between rows in order to compensate for low moisture levels. In the wide-spaced rows, the soil moisture supply is not exhausted as rapidly as in narrow rows (Brown and Shrader, 1959). Intra-row competition prevents excessive vegetative growth, and the laterally developing roots have to grow farther to reach moisture. They therefore continue to find available moisture between the rows later in the season, when it can be used for grain production – provided the distance between the rows has been well adjusted to the available soil moisture. The heads are small but relatively numerous under these conditions, and maturity is more uniform than with plantings in close-spaced rows, with wide intra-row spacings.

An alternative design to achieve the same purpose was tested by Blum and Naveh (1976). Plant competition was promoted by sowing sorghum in double rows (40 cm between rows of a pair), and 160 cm between row pairs, as compared to regular spaced rows (100 cm between rows), with the same number of plants per unit area.

In the double-row configuration, the effect of competition was first observed about 20 to 35 days after emergence: reduced tillering and LAI, and reduced stover dry matter/plant. During the boot to full bloom growth stage, less soil water was extracted; consequently, more water was available during the grain-filling period. The number of panicles/plant was smaller, but the number of grains/plant and seed weight were increased. Grain yield was significantly increased in two out of four experiments.

It might be assumed that the wide row spacings, by exposing large areas of bare soil to radiation, would increase moisture losses due to evaporation thereby defeating the purpose of the wider spacings. However, under dryland conditions, evaporation is influenced more by the moisture supply at the soil surface than by radiation. Therefore, once the upper soil layer has dried, further moisture losses by evaporation become negligible. Under these conditions, wide rows are not more conducive to greater water loss by evaporation than are narrow rows.

Skip-row patterns: cotton has usually been planted in single rows spaced from 80 to 120 cm apart. However, in semi-arid regions, experience has shown that acceptable yields of rainfed cotton can be obtained with less risk of failure by using lower plant populations arranged in various skip-row patterns. Several patterns are in use: sowing every second row, sowing two rows out of three, sowing one row out of three, and sowing two rows out of four.

The basic principle of skip-row patterns is that row omission provides greater soil volumes and more available water to individual plants, especially at the critical flowering period (Jordan, 1983).

Varieties

The need to adjust population levels for a given crop grown in different climatic zones can also apply to different varieties of the same crop.

Guler (1975) found that some varieties had different optimum plant population densities at the same locations, while other varieties responded uniformly at a given population level in several locations. For example, Mohammad et al. (1982) found that shorter statured, semi-determinate, early maturing cultivars are most responsive to narrow rows and/or high populations.

Other objectives of adjusting population rates

The Dryland Agriculture Technical Committee (1979) has pointed out that seeding rates in the row and row spacings have traditionally been used for two purposes, neither actually related to the best plant population for highest yields. Greater than optimum rates are employed to provide ground cover for wind and water erosion control. Close row spacings are often preferred to improve competition with weeds. These concepts may be very useful under favourable moisture régimes, but where moisture is limiting, they will contribute to lower yields.

Moisture supply not limiting

Spatial arrangements may affect the efficiency of radiant energy interception or of moisture utilization.

Radiant energy interception. The main effect of spacing on yield is believed to be largely due to differences in radiant energy distribution. Closer and more uniform plant distribution should increase the proportion of radiant energy which is intercepted by the plants and reduce that reaching the soil surface. In experiments with maize, it was shown that the ratio of the net radiation at the ground to that above the crop was lower, the higher the rate of planting; with the same population, the closer the inter-row spacing was, the lower became the ratio (Yao and Shaw, 1964b). It has been estimated that 60 cm inter-row spacings might increase the energy available for photosynthesis by 15 to 20 % compared with 100 cm rows (Denmead et al., 1962).

Moisture utilization. Tanner and Lemon (1962) have shown that, when soil moisture is available and a substantial crop cover shades the ground, most of the net radiation is used for evapotranspiration. Therefore, differences in net radiation resulting from different plant populations and row spacings should also result in differences in water use and water use efficiency.

In trials carried out by Yao and Shaw (1964a) it was found that, in maize fields

when inter-row spacings were maintained constant, doubling the plant density increased water use, but the increase in water use was much smaller than the increase in plant density. The narrowest row spacing (52 cm) used significantly less water than did wider spacings, with the differences in water use between treatments becoming more apparent as the season progressed. The highest efficiency of water use was achieved at the narrowest spacings with the double plant density.

With sorghum grown with two or more irrigations, narrow rows produced considerably more grain than did wider rows with identical plant populations. Soil moisture was extracted more rapidly, after irrigation, directly under plants than midway between rows, for rows more than 35 cm apart. It is therefore assumed that a more uniform extraction of soil moisture under narrow rows led to their greater grain producing ability when water was not limiting (Grimes and Musick, 1960).

In cotton, as in other row crops, the wide rows traditionally used were dictated for the convenience of subsequent tillage operations and harvesting. The required plant populations, which ranged from 60 000 to 500 000 plants per ha, were achieved by varying distances between plants within the rows.

With chemical weed control, and once-over mechanical harvesting, wide spacings have become obsolete and the tendency is to adopt narrower spacings and higher plant populations, provided water is not limiting.

In addition to higher yield potential, the new planting patterns have the advantage of earlier maturity, reduced cost of weed control and easier mechanical harvesting (Jordan, 1983).

Irregular spacings in the row

In order to improve the efficiency of cultivation for the control of weeds, crops may be sown in such a way that rows of equal width run in two directions. This is achieved by *check-row planting*, which allows cross cultivation. This method, which considerably slows sowing operations, has lost much of its utility with the advent of improved weed control practices, both mechanical and chemical.

There are relatively few experiments comparing uniformly distributed plants in the row with hill or pocket groupings. Uniform spacing generally gives a greater yield than hill groupings under favourable soil moisture conditions. However, when moisture is limiting, the advantage may be small or nil (Dungan et al., 1958). Donald (1963) suggests that the advantage of the uniform spacing under favourable conditions is due to reduced competition for light; when soil moisture is lacking, light is no longer the limiting factor, and the advantage of uniform spacing is lost.

Row direction

Very few investigations on the effect of row direction on yields have been made. The

few results have been surprisingly similar with different crops grown under widely different conditions.

In Australia, yield increases in dry-matter production by wheat of 6.5 and 11%, respectively, were obtained in two experiments with N–S sowings as compared to E–W sowings (Santhirasegaram, 1962). In the former USSR, spring wheat sown N–S produced from 100 to 300 kg/ha more than when sown E–W. It is assumed that sunlight and moisture were used more fully in the N–S than in the E–W rows, and that the plants in the N–S rows were the less subject to excess heat (Perekaljskii, 1951).

In India, it has been found that maize planted in a N–S direction yielded significantly more grain and forage than when it was planted in an E–W direction (Dungan et al., 1958). Similarly, in Illinois, spring oats drilled in a N–S direction yielded slightly more grain than when it was drilled in an E–W direction; the advantage of the N–S row increased as inter-row spacings increased (Pendleton and Dungan, 1958).

Whilst a full explanation for these results is not available, it is possible that sunlight and the amount of reflected light are influenced by row direction, with N–S rows enjoying better lighting than the northern exposure of the E–W rows.

In the past, sowing on ridges was exclusively practised in furrow irrigation. Ridge planting is now frequently used for rainfed crops (Ch. 14). One system, the ridge–furrow system, also called inter-row water harvesting, was studied at several research centres in the Indian arid zone, with the basic objective of increasing water availability by concentrating water in the planting furrows (Singh et al., 1973). One aspect that was studied was the possibility of controlling incident radiation and wind action in the furrows, and more specifically, using shading as a means of controlling incident radiation in the field and the resultant loss of moisture.

In very-low-rainfall areas, the direction of the dominant winds was found to be probably the major factor to be considered. In the Indian arid zone (Jodhpur, Rajasthan) the NW–SE row direction is at a right angle to the dominant wind flow; by sowing on ridges oriented in this direction, a net reduction in wind flow, a decrease in soil surface temperature of 3–4°C, and a consequent increase in relative humidity was obtained. Water storage was about 25–40% higher as a result of lower soil surface temperature and reduced wind flow with consequent improved yields. By contrast, shading in the E–W aspect was practically nil (Singh and Bhati, 1988).

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CHAPTER 16

Crop Sequences and Associations

Crop rotations

Crop rotations in semi-arid, rainfed agriculture are restricted by the relatively small number of crops suitable for these conditions, because of ecological and economic constraints encountered.

The major crops of these areas are listed in Table 16.1.

Objectives of crop rotations

A well-planned crop rotation should have the following advantages over monoculture or a haphazard succession of crops; it should:

- maintain, and even improve, soil fertility and efficient use of nutrients;
- prevent the build-up of pests, weeds, and soil-borne diseases;
- control soil erosion;
- ensure a balanced programme of work throughout the year;
- prevent or limit periods of peak requirements of irrigation water;
- conserve moisture from one season to the next;
- be sufficiently flexible to adjust to changing market conditions.

Principles of crop rotations

Crop sequence per se is not necessarily beneficial. Sorghum, for example, can follow almost any crop, but few crops grow well when sown after sorghum. Hughes and Metcalfe (1972) have shown that when wheat followed sorghum, the combined yield of the two crops was less than that obtained from two successive crops of wheat or of sorghum.

For crop rotations to be beneficial, economically viable in the long run and ecologically sustainable, certain principles need to be adhered to. These are:

TABLE 16.1

Major rainfed crops of semi-arid areas

	Cool-weather crops	Warm-weather crops
Cereals	wheat, barley, oats	maize, sorghum, millets
Legumes	chickpeas, horse beans, peas, lentils, vetches	beans, pigeonpea, cowpeas
Oil crops	linseed	sunflowers, groundnuts, safflower, sesame
Industrial crops	sugar beets	cotton

- (1) Alternate growing of crops with differential ability to absorb nutrients from the soil or having different depths of rooting systems.
- (2) Alternating crops susceptible to certain diseases, with those that are resistant.
- (3) A planned succession of crops that takes into account any detrimental or beneficial effects of one crop on the following crop. These effects may be due to toxic substances, effects on nutrients supply, build-up of organic matter, soil structure, soil micro-organisms, or residual soil moisture.
- (4) Alternating soil-exhausting crops with crops that contribute to the improvement of soil fertility.
- (5) Alternating crops with different peak requirements of labour, water, etc.

Are crop rotations obsolescent?

Crop rotations were once considered to be the essential basis of a stable agriculture. They were the only available means of preventing the deterioration of soil fertility and of achieving relatively high and stable yields. By contrast, monoculture of the so-called cash crops was considered the epitome of backward, self-defeating farming methods which resulted in an exhausted and usually eroded soil.

The technological innovations in agriculture justify a re-appraisal of the need and justifications of crop rotation in the following connections:

(1) *Soil fertility*: At a time when chemical fertilizers were non-existent, nitrogen fixation and the application of farmyard manures were the only ways of ensuring a high level of soil fertility and providing essential nutrients for crops. At present, chemical fertilizers are generally plentiful and relatively inexpensive; by contrast, the costs of growing legumes and handling stable manure have increased steeply. Heavy applications of fertilizers also increase the amounts of organic residues that can be returned to the soil.

(2) *Prevention of build-up of soil-borne diseases, pests and weeds*: The increasing array of fungicides, pesticides, and herbicides, available to the farmer, has provided him with tools for protecting his crops which are far more effective than the simple

rotation of crops. There are a number of serious soil-borne diseases for which crop rotation never was effective.

(3) *Control of soil erosion*: Minimum tillage, stubble-mulch farming, and sowing on the contour, make it possible to prevent soil erosion, even in monoculture.

(4) *Ensurance of a balanced programme of work throughout the year*: This was one of the great advantages of crop rotation when most farm operations were carried out with animal power and manual labour. With the mechanization of agriculture and the use of increasingly specialized, sophisticated, and expensive, machinery, only the farmer who grows at the most two crops, can afford the expense of purchasing and maintaining the equipment that is required to grow a crop economically. Furthermore, the farmer growing only one or two crops becomes a specialist in them, with a high level of know-how and competence. In these respects the farmer growing a number of crops in rotation is at a disadvantage.

As a result of recent innovations in agricultural technology, including those mentioned above, the historical view that a planned rotation of crops is essential for the maintenance of soil fertility and efficient water-use is no longer generally accepted. The new attitude is summarized by Pendleton (1966) as follows: "The trend towards monoculture has not resulted in great losses of water, soil and yields, as predicted not too many years ago. To a large degree, this may be attributable to technological advancement. This new era of 'crop specialization' has resulted in more total food or fibre from a given farm, and therefore more efficient use of water".

Limitations of monoculture

Before crop rotations can be abandoned as an essential element in good farming, a number of limitations must be overcome.

Nutrient supply

Crop sequences allow a more efficient use of soil nutrients since crops differ in their nutrient requirements and their root systems, thereby exploring different soil levels. Cereals deplete soil nitrogen, while legumes may enrich the soil in nitrogen but deplete phosphorus.

For rainfed crops, under semi-arid conditions, deficient soil moisture limits the amounts of chemical fertilizers that can be applied and, especially for nitrogen, may even make their use impracticable. Low yield levels also make the use of heavy fertilizer doses prohibitive. In the discussion on cropping systems adapted to these conditions (see p. 757), it will be shown that rotations including forage legumes are still frequently the most economical solution to this problem.

Fertilizers are not cheap or easily available everywhere, and are especially costly in the less developed semi-arid regions that are remote from industrial centres. A crop that supplies forage *and* nitrogen may be able to justify itself economically. The

organic nitrogen from symbiotic fixation may be more suitable than mineral nitrogen under conditions of limited moisture supply, being released more gradually, to become available at a time when conditions are favourable both for microbial activity and plant growth.

In the semi-arid zone of West Africa, subsistence farmers who cannot afford chemical fertilizers, allow the soil to lie fallow during the dry season in order to obtain a supply of nitrogen through mineralization of soil organic matter (Focht and Martin, 1979).

Moisture supply

Periods of fallow between crops is considered a necessity in fringe rainfall areas to store precipitation for the following season's crop; it is the only way to ensure sufficient water for obtaining an acceptable yield level under conditions of limited rainfall (Fig. 16.1). An additional incidental benefit is the weed control achieved.

Disease control

It is in relation to crop diseases, and in particular, soil-borne pathogens, that the limitations of monoculture are most evident, and the contribution of well-planned crop sequences is most beneficial.

Monoculture favours the build-up of specific diseases and pests, as well as the development of resistant strains.

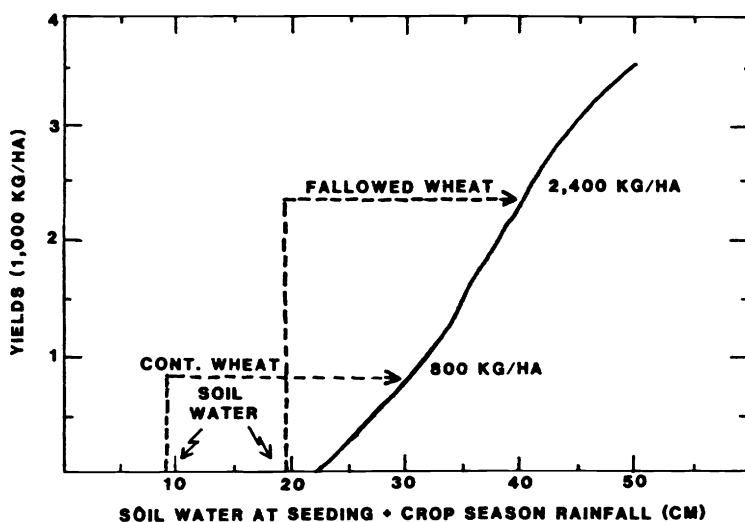


Fig. 16.1. Wheat yield expectancy at North Platte, Nebraska, from 1921 to 1967. Fallow is necessary in the semi-arid Central Great Plains because the water requirement for initial grain development of winter wheat begins at about 220 mm of ET in relation to 300–560 mm/year precipitation. Grain yields then increase about 105–180 kg/ha per 10 mm after minimum water requirements are satisfied. From Greb (1983). With permission of American Society of Agronomy, Inc.

It is generally accepted that crop sequence per se is not capable of sufficiently reducing diseases caused by polyphagous pathogens, especially those with marked saprophytic ability or very persistent organs of survival. However, a combination of planned crop sequence and specific cultural practices has been successful in controlling some of the more destructive soil-borne diseases. Even when full control is not possible, as in the case of *Phymatotrichum omnivorum*, which, as its name indicates, can parasitize some 200 species of weeds and cultivated crops, a well-planned crop sequence will, in many cases, slow down pathogen build-up in the soil, and thereby weaken the incidence of a disease or delay the need for chemical treatment (Palti, 1981).

For example, in arid regions, a root rot of cotton, caused by *P. omnivorum*, is very common. The incidence of the disease can be considerably alleviated by including cereals in the crop rotation. In Texas, by sowing cereals in a four-year crop rotation, seedling mortality of cotton was reduced from 40 to 5% (Curl, 1963).

Palti (1981) distinguishes between fallowing out of sheer necessity, because of insufficiency of annual rainfall, and fallowing by choice, as a means of keeping fields free from soil-borne diseases ('dry fallowing').

Fallowing by choice "is largely an economic consideration, taking into account revenue from crops that could be grown during the fallow period, alternative methods of reducing pathogen populations in soil, and benefits of fallowing for succeeding crops".

Dry fallowing is effective in reducing soil disease and nematode populations because the metabolic rates of these pests are high in warm dry soils and their food reserves are rapidly exhausted under these conditions (Van Gundy and Luc, 1979).

Dry fallowing for pathogen control is frequently aimed at nematode control. Combined clean fallow and growing barley has reduced populations of *Meloidogyne incognita* in cotton after less than a year (Carter and Niesto, 1975) and one fallowing period between rice crops was sufficient to reduce the root lesion nematode (*Pratylenchus indicus*) to acceptable levels (Prasad and Rao, 1978). Other species, such as *Heterodera shachtii* require longer periods (Fig. 16.2).

Dry-season fallowing has been successful in Africa, in regions with dry seasons, in controlling brown rot (*Pseudomonas solonacearum*) (Waller, cited by Palti, 1981).

Amir et al. (1988) reported increases of 104–220% in wheat yields as a result of dry fallow in the Northern Negev of Israel, with below-average rainfall (239 ± 96 mm). This increase was not due to improved moisture supply, as the soil was completely dry at the time of sowing. The fallow had no significant effect in years with above-average rainfall.

An appropriate choice of crops in the crop sequence can also contribute to disease control. For example, in California, growing cotton in rotation with paddy rice has proved very effective in controlling cotton wilt (*Verticillium dahliae*) (Butterfield et al., 1976).

On the other hand, crops that are susceptible to many multi-host diseases are

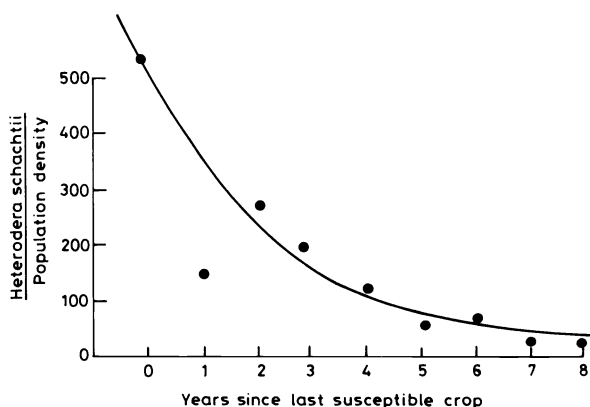


Fig. 16.2. Average nematode (*Heterodera schachtii*) population density, as related to number of years since the last susceptible crop was grown. About 5–6 years is the shortest period of rest from sugar beets or other susceptible crop that will be required in the rotation to reduce the nematode population to the level where the cultivation of sugar beets is economical. From Caveness (1959). By permission of the American Society of Sugar Beet Technologists.

dangerous predecessors in crop sequences. For example, soybeans may leave residues infected by almost all major soil-inhabiting pathogens with wide host ranges. Some crops that are not affected by certain pathogens may raise the level of the disease in the following crop. For example, turning under green manure before sowing cotton or potatoes, has increased attack by *Rhizoctonia solani* and *Pythium* spp. Apparently, decaying fresh plant material is more favourable for colonization by these pathogens than by saprophytes (Palti, 1981).

The efficiency of crop rotation in reducing the severity of a number of soil-borne diseases, is ascribed not only to the 'starvation' of the pathogen in the absence of a suitable host, but also to the stimulation of antagonistic properties of the soil microflora, by the non-hosts and their residues (Patrick and Tousson, 1965).

Just as the repeated cropping of a susceptible host causes a build-up of the population of a plant pathogen, it is assumed that the repeated turning under of certain crop residues may favour the build-up of a suitable antagonist. In addition, the host may be less susceptible to attack under the more favourable conditions of soil fertility resulting from the decomposition of organic matter.

The farmer who grows the same crop continuously cannot be sure that his yield levels are not declining gradually. Such a decline will be masked by annual yield fluctuations due to environmental factors. Worse still, yields may drop suddenly and steeply, as the result of a build-up of disease organisms to epidemic proportions. Even in a crop such as cotton, which is relatively insensitive to continuous cropping, yields may decline after a period of time. In Australia, cotton grown continuously on previously virgin land, maintained its yield level unimpaired for eleven consecutive

years; after that, yields declined gradually, irrespective of the rates of fertilizer application (Phillips, 1963).

Certain crops, such as flax (*Linum* spp.), guayule (*Parthenium argentatum*), and brome grass (*Bromus inermis*), are particularly subject to 'soil sickness'; stands become sparser and yields decline when the crop is grown continuously in the same soil. The conditions are usually species specific, and other crops grow well in the same soil. It is possible that other or additional factors, besides phytotoxic substances, are involved (Patrick and Tousson, 1965).

Under irrigation

Under continuous irrigation, there is a simultaneous build-up of diseases, pests and weeds, and a breakdown of soil structure. Whilst many effective fungicides, pesticides, and herbicides are available none of these has yet enabled full control of the diseases, insects and weeds, that are apt to be encountered in irrigated fields. Their maximum effectiveness is achieved only when they are integrated in a system of crop management which includes crop rotation.

The most effective way of revitalizing the soil, achieving sanitation, and improving soil structure, is the inclusion in the rotation of rainfed or lightly irrigated crops that completely dry out the soil. If, in dryland agriculture, legumes play a major role in improving soil fertility, in irrigated agriculture it is the cereals which are the key to improved sanitation and soil structure.

Wet fallowing, i.e., leaving the land free of crops while irrigation is intermittently interrupted (generally for a few weeks) is intended to favour the germination of pathogen propagules in or on the soil and thereby expose them to attack by saprophytes. This approach is not effective for pathogens whose propagules are only activated by exudates from their hosts. It has been effective for pathogens forming sclerotia, such as *Sclerotium rolsii*, *Verticillium dahliae*, *Sclerotinia* spp. Wet fallowing has also been partly successful in *Pythium myriotylum*, one of the causes of pod rot in groundnuts, and for the control of pathogens infesting crop residues on the soil surface (Palti, 1981).

Weed control

When a crop is sown year after year in the same field, a specific weed flora will establish itself, comprising those species that are best able to complete their growing cycle under the management practices adopted for that particular crop. For example, annual grassy weeds, such as wild oats, are favoured by the same conditions under which wheat is grown, such as time of planting and fertilizer application; much of their seeds mature and scatter before the wheat is harvested; the rest contaminates the wheat seed, from which some grassy weed seeds are difficult to separate. By growing in sequence crops that have different life cycles, and require different management practices, crop-specific weed flora can be effectively controlled. For example, a hay crop, following wheat, makes it possible to mow the weeds before they mature seed;

a summer crop makes it possible to destroy winter weeds during the fallow period following the wheat harvest, etc.

Economic considerations

The need for specialized, expensive equipment is an important argument that cannot be overlooked, but must be considered within an overall economic appraisal of the cropping systems. This problem can also be overcome by employing contractors for certain operations such as mechanical harvesting. The most desirable crop rotation is the one that gives the maximum profit, on a sustained basis with the least fluctuations, over a period of years.

When a crop, such as a forage legume, that has a favourable effect on the yields of the succeeding crop, is included in the rotation, the total yield of the benefiting crop may be increased up to a point, although the actual area devoted to the crop is reduced. This is the so-called complementary effect – indicating that the inclusion in the rotation of crops that raise soil fertility or improve sanitation does not necessarily reduce the income from cash-producing crops.

Against the economic advantages that are claimed for monoculture, are the lesser fluctuations and smaller risks involved in growing a number of crops, as price and weather fluctuations do not affect all crops equally. Thus farmers will have to balance greater stability in income, and thus lower risks, against the possibly higher income obtainable from a single crop.

Where irrigation farming is practised, the possibility of using irrigation water efficiently for many months of the year, as is possible when several crops are grown, may be the overriding economic factor. With a single crop, it is the peak period of water requirement that will limit the area that it is possible to cultivate with the amount of water available.

Summing up, it can be stated that the farmer is no longer as dependent on crop rotation for maintaining high levels of production as he was in the past. However, a well-planned crop rotation still has important functions in soil sanitation and fertility, weed control, regulation of labour and water use, and stability and security of income, so that in many cases it can confer economic advantages over monoculture.

Whatever the advantages of cropping sequences, it is however unlikely that monoculture will be abandoned in industrialized countries, mainly because the most important criterion is production efficiency measured in terms of production units per man-hour (Klassen, 1979).

Types of crop rotation adapted to arid and semi-arid regions

Whilst crop rotations may vary considerably in different regions, depending on tradition, the type of crops grown, local economic factors, etc., certain prototypes have developed which will be discussed here, as well as the fundamental principles on which they are based.

Winter-rainfall regions with mild winters

Transition regions between aridity and semi-aridity (250–400 mm rainfall). In the transition region between aridity and semi-aridity, where the average precipitation fluctuates between 250 and 400 mm, rainfed crop production becomes possible, but is fraught with great dangers. In favourable seasons, when precipitation is above average, exceptionally good yields of grain can be obtained as a result of fertility build-up during the seasons of low rainfall and crop failure. Large areas are usually ploughed up and sown, to become dust bowls when there is a succession of drought years.

The principal crop rotations followed in these areas are:

(1) *Continuous wheat* (or barley), with crop failures during the dry years serving as unplanned fallow periods. If good yields are to be obtained during the favourable seasons, heavy nitrogen fertilizer applications are essential. Inputs are therefore high, with a low probability of success.

(2) *Cereal-fallow*: In Australia, in the wheat-growing regions with an annual precipitation of 250 to 375 mm, experience shows that the fallow-wheat sequence usually assures the farmer of a crop, whereas continuous wheat would generally be a complete failure (Callaghan and Millington, 1956).

The practice of alternating winter fallow with a crop, in a two-year cycle became widely adopted in the 1920's in southern California and remains in use for nearly all dryland grain cropping. The commonly accepted name of summer fallow is a misnomer as actually the dry summer season is a period of total water loss in the winter-rainfall region.

Most years, winter fallow increases the moisture supply available to the crop and assures economic grain production (Luebs, 1983). In the low-rainfall regions, a succession of drought years is a frequent occurrence, and therefore even the additional moisture stored by the fallow may be insufficient to ensure a good crop. Under these conditions, cultivated fallow may promote an initial stimulation of yields, but in the long run it usually has adverse effects of which wind and water erosion are the ultimate outcome. This system also requires fairly high inputs with uncertain returns.

Response farming. Most rotations lack flexibility, and cannot be adjusted to the variable conditions encountered in low-rainfall dryland farming. In response cropping, systems are devised that enable the farmer to cope with seasonal rainfall variability, that normally ranges from one-third to double average precipitation. "Response farming aims at anticipation of these swings, and the modification of farming systems in ways calculated to maximize production returns per unit rainfall actually received" (Stewart, 1988).

A rotation in which fallow has been replaced by leguminous leys, and is based on alternating a period of two or more years of annual, self-seeding legumes – grazed by

cattle or sheep – with one or more years of grain crops, has been tested for fringe semi-arid conditions.

This system has a built-in auto-regulatory device ensuring a yearly, albeit fluctuating, income. In the good rainfall seasons, the legume and the stubble of the cereal crop produce year-around grazing (provided the number of head of stock is properly adjusted to the carrying capacity), whilst good grain yields are harvested. In the poor rainfall seasons, the relatively low production of the legumes is supplemented by grazing the cereal fields which have no prospect of producing a satisfactory grain crop. What would have been a total loss in an exclusively grain-producing system, will give a fair yield of forage – even in conditions under which no grain is formed.

In the semi-arid tropics of northern Australia, a legume-ley no-till system has given very good results. The system is based on:

- a rotation of one to three years of self-seeding legume followed by maize or sorghum;
- the crops are sown directly into the pasture, which is killed using a herbicide;
- the pasture re-establishes itself from hard seed within the stand of the crop;
- the cattle graze on native grass pastures during the wet season, and on the legume-ley and crop stubble during the dry season.

It was found that after one year, the legume provided 40–60 kg/ha N equivalent; maize yields were 20% more than a conventionally grown crop; soil temperature was reduced by 3–4°C. The cattle gained weight even during the dry season (El-Swaify et al., 1984).

One such system of response farming has been tested in Israel, in a fringe rainfall area in the Northern Negev, with a mean average winter rainfall of 250 mm. The legumes may produce from 100 to 500 feed units (FU) per hectare even with a yearly rainfall of no more than 60–100 mm; with 200 mm, which is insufficient for grain production, the cereal may still produce 100 to 1300 FU/ha. In a good year, the legumes will produce around 2000 FU/ha and the grain stubble will provide another 300–500 FU/ha.

This integrated system of animal husbandry and cereal cropping also has the advantage of relatively low inputs: the annual legumes are self-seeding, so that no tillage, or only a minimum, is required. Only phosphatic fertilizers are needed, and if applied in excess of current requirements, the residues are not wasted. The legumes provide all the nitrogen that is needed by the cereal crop, but in a very good year additional nitrogen may be top-dressed. The cereal can be seeded into the legume stand by a chisel drill without additional tillage; excessive legume volunteer plants in the cereal can be controlled by herbicides. Grain volunteer plants in the legumes provide balanced grazing. Perennial weeds such as johnson grass and couch grass, are kept in check both by the grazing and by the competition of the cereal crop.

The effectiveness of the whole system depends on how animal numbers are in balance with the fluctuating forage supply.

Semi-arid regions with 400 mm winter rainfall and above. Traditional crop rotations. The main objective of arable farmers in these regions is usually the production of cereals, preferably wheat. In the more problematic areas, wheat is replaced by barley.

Farmers are usually aware that continuous cereal growing invites disaster, and therefore most of the wheat – or barley in the drier regions – is grown in alternate years. As normally only a single crop can be grown each year, the two-course rotation predominates throughout the region. Some of the variations of these rotations are: wheat–weed fallow; wheat–cultivated fallow; wheat–pulses (beans, lentils, chick-peas); wheat–cultivated summer crops; and wheat–barley. When three- or four-course rotations are practised, they usually take the form of wheat–barley–fallow, or of wheat–pulses–barley–fallow. A common factor of these rotations is that they do not include any crops for improving soil fertility, which is usually at a very low level. The farmer does not even adhere rigorously to any of these rotations. If the rains are early and abundant, and the season bodes well, he will usually be tempted to sow a wider area to wheat than was allocated in the rotation.

Cultivated summer crops have the advantage of aiding in the control of weeds, which may present serious problems in continuous wheat growing. However, when the summer crop has a detrimental effect on the moisture status of the soil, it may offset any beneficial effect in regions in which soil moisture is the limiting factor.

Improved crop rotation. The traditional crop rotations described above are all exhaustive and make no contribution to soil fertility. The basic problem is, therefore, to devise a type of crop rotation that will raise the level of soil fertility, thus making it possible for the following crop to benefit fully from the favourable moisture régime prevailing during its growing period.

It is frequently assumed that pulses are desirable preceding crops for winter cereals, and it was originally thought that extending the area under pulses would have a beneficial effect on soil fertility. Many Ministries of Agriculture in the semi-arid regions have adopted the inclusion of pulses in the rotation as an official policy aimed at improving overall productivity. However, results are always disappointing, as harvesting a seed crop from the legume usually results in a drop of at least 30% in the yield of the following wheat crop, as compared with wheat following fallow. The legume removes more nitrogen than the root nodules produce. The soil is also left in a very unfavourable physical condition, and weed infestation in the subsequent cereal crop is heavier than usual.

In research on the effect of leguminous crops in the rotation, Lyon (1936) has shown that, when cereals for grain are grown after pulses (beans, soybean, etc.), yields were only 47% of those obtained after legumes that had been grown for hay (red clover, alsike clover) (average results of eight years). In soils in which cereal grain crops and leguminous hay crops alternate, there was after eight years, an increment of 500 to 650 kg/ha of nitrogen; whilst after alternating cereal and leguminous grain-crops, there was even a small deficit, of 50 to 100 kg/ha of N, after the same trial period.

Heichel and Barnes (1984) confirm that when a grain legume is harvested, there is often little, if any, net addition of N to the soil.

Leguminous crops that are not allowed to mature seed, but are used for pasture, soiling, hay, silage, or for turning under as green manure, have been shown to be very important for improving soil fertility. They also enhance the response of the winter cereals to other factors affecting production.

At first, green manures were considered the ideal solution for rapidly raising the level of soil fertility. On the whole, the results obtained in semi-arid conditions have been disappointing, and green manures have generally shown little, if any, benefit over results derived from leguminous forage crops. Where green manures have been beneficial, the increase in yield rarely justified the loss of a cropping season or the risks and expenditure involved. However, legumes harvested for forage, before producing seeds, have proved very effective in increasing yields.

Under conditions in which the inclusion of legumes in the crop rotation increased the yields of the subsequent cereal crop, residual soil moisture after removal of the legume may be high, and not much less than that after fallow, as is shown in Table 16.2.

The earlier the legume was harvested, the higher was the amount of residual moisture (Fig. 16.3). Green manure and silage were as effective or nearly as effective in conserving moisture as was cultivated fallow. By contrast, when a deep-rooted legume crop such as lucerne or sweet clover is turned under for green manure, the soil has usually dried out to a depth of several feet.

The value of fallow in the crop rotation. Fallow as a means of increasing soil moisture in the higher-rainfall regions is not of overriding importance, and as a means of maintaining soil fertility is not very effective. In southern California, from 30 to 40% of the organic matter has been lost from the surface 25 cm after 50 to 70 years of grain cropping, mostly in the alternate fallow–grain system (Luebs and Laag, 1964). In south Australia, the inherent fertility of the red–brown soils was quite rapidly

TABLE 16.2

Effect of fallow and legumes in the rotation, on amount of residual moisture at the time of sowing of the following wheat crop (Arnon, 1961)

Preceding crop	Amount of residual moisture in soil (30 to 120 cm depth)	
	m ³ per ha	in percentage of control
Fallow	3500	100
Green manure (fenugreek)	3500	100
Silage (horse-beans)	3230	92
Hay (vetches)	2950	84
Grain (fenugreek)	2520	72

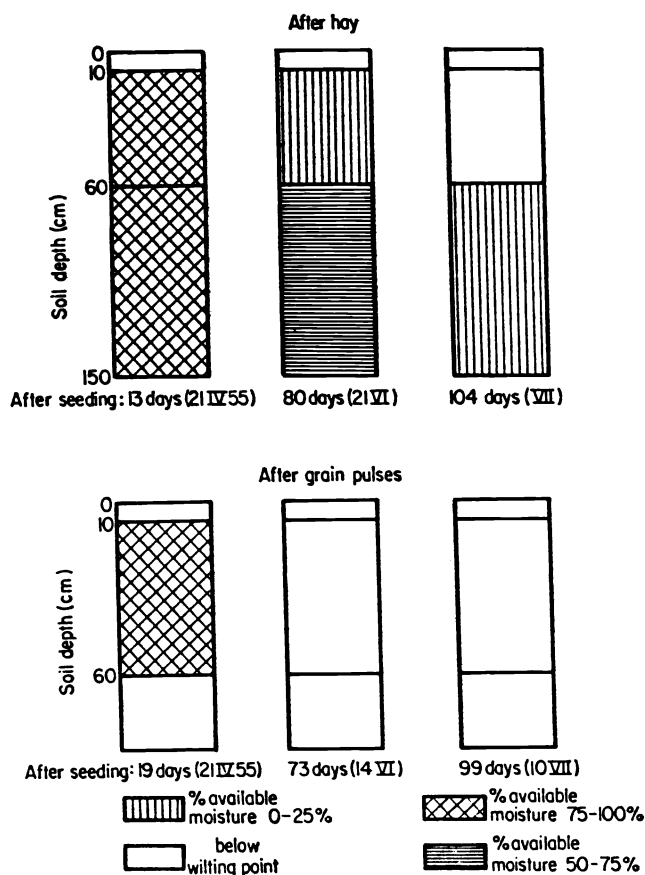


Fig. 16.3. Effect of the stage at which a legume is harvested on the amount of residual soil moisture available to the following crop. From Arnon (1961).

depleted by the bare fallow–wheat rotation which was at first widely practised. The situation improved only after the introduction of subterranean clover pastures into the rotation, which rapidly restored the productivity of worn-out wheat soils.

Simply resting the soil, even for a period of only one year ('weedy' fallow) is detrimental to yields and a very poor antecedent for the winter cereals. The depressing effect is due mainly to weed competition, for a cultivated fallow does not show the same negative influence.

Part of the value of fallow is that satisfactory moisture conditions may coincide with temperatures that are favourable for nitrification, so that sufficient amounts of nitrate nitrogen may be made available for the following crop. Fallow is also effective in accumulating nitrate in the soil. In a semi-arid winter-rainfall area, fallow increased available nitrogen from five- to sixfold over recent cropping (Littlejohn,

1956). However, the benefits of cultivated fallow in regions of adequate rainfall are usually overrated and, except in years of unusually low rainfall, the yields obtained after a leguminous hay crop are generally higher than those obtained after a cultivated fallow.

In summary it may be said that the most promising approach towards raising the level of soil fertility in semi-arid regions of sufficient winter rainfall (400 mm and above) is the inclusion in the rotation of a leguminous forage crop. When the legume is cut before seed is formed, the amount of plant nutrients removed from the soil is relatively small, whilst the soil is enriched in nitrogen and organic matter. Weeds are cut before flowering and are therefore well controlled. The soil can be ploughed when still moist and an excellent tilth is obtained.

As regards the types of rotation, the areas devoted to a soil-improving crop may vary from one-third to one-sixth of the total area, with a tendency to devote as large an area as possible to the winter cereal in the crop rotation. Hence we get a plethora of three-, four-, five-, and six-year crop rotations, with various sequences of crops, in which the winter cereals occupy an important position. The best overall results in Israel have been obtained with the following three-course rotation:

First year – winter cereals (wheat, barley, or oats).

Second year – summer crops (sorghum, maize, sunflowers, sesame, or chickpeas).

Third year – hay crops (vetch, annual clover, etc.).

A different sequence is sometimes adopted, in which the winter cereal follows the summer crop. This is justified when fields are infested by grassy annuals, such as *Phalaris* and wild oats. In such a case it is the summer crop which is assigned the best place in the rotation, thereby benefiting from residual moisture after the legume and from the favourable nitrogen status resulting from the latter.

In the summer crop course, the crop subsists entirely, from sowing to harvest, on stored moisture from the winter rains. As only a single crop can be grown a year under the prevailing climatic conditions, the winter fallow does not entail the loss of a year's crop. The fallow is also relatively efficient, as the water is stored during the cool season, when evaporative demand is relatively low. The major condition for success is a weed-free fallow. Formerly, this objective was difficult to achieve, because opportunities for timely weed control during the rainy season are rare, and coping with a heavy weed growth was always costly in terms of water lost. These problems have disappeared completely: a single herbicide treatment at the beginning of the rainy season can keep the fields weed-free until the time for sowing in early spring.

The most successful crop for these conditions is sorghum. In California, sorghum grown solely on water stored in a clay loam that was moist to a depth of 3 m, produced grain yields of 8–9 t/ha, similar to those of an irrigated crop (Feres-Castiel, 1976).

In Israel, yields of dryland hybrid sorghum were lower than with supplemental

irrigation, but still very high (5 t/ha). Other summer crops successfully grown on stored water are cotton, tomatoes for processing, melons, watermelons, pumpkins, and cowpeas.

Summer-rainfall regions in the middle latitudes

The crop sequences depend primarily on the amount of precipitation. For example, in the Pacific Northwest, dry-farmed areas are divided into three zones (Papendick et al., 1983):

- Summer fallow zones (annual precipitation 250–350 mm); the crop sequence practised is alternate winter wheat–fallow.
- Intermediate zones (annual precipitation: 350–450 mm). Annual cropping is possible when rainfall is above normal. The usual system is to produce two or three crops between fallow periods.
- Annual crop zones (>450 mm). Winter wheat is grown in rotation with peas, lentils, and spring cereals, such as wheat or barley.

Continuous cereal growing. In the semi-arid regions of the world in which grasslands have been ploughed up for crop production in modern times (as in the Great Plains of the USA) and an adequate moisture supply is assured, the general tendency is to practise monoculture, with wheat grown continuously for long periods. In the areas with relatively favourable precipitation, alternate wheat–fallow is practised only occasionally – either when weed infestation has become a serious problem, or when exceptionally deficient soil moisture at the sowing time makes wheat sowing too hazardous.

Experience has shown that the accumulated fertility of soils which have always been under native grass before they were ploughed up, enables continuous wheat cropping without declining yields for thirty years or more – provided weeds are kept under control (Harper, 1959). However, during this period, at least half the original organic matter and nitrogen will have disappeared, and so it is difficult to prophesy whether (and, if so, when) continued monoculture will start to have undesirable results. Even if a satisfactory level of soil fertility is maintained, sooner or later a build-up of grassy weeds occurs, which makes wheat growing unprofitable. Under these conditions, a three year rotation of fallow–wheat–sorghum was found to give good weed control, as well as providing for efficient use of water and nitrogen and giving satisfactory protection against wind erosion. It also gave a higher gross income than a fallow–wheat–wheat rotation (Ramig and Smika, 1964).

Alternating wheat and fallow. In the rainfall-deficient areas, the main importance of a cropping sequence is to provide the minimal quantity of moisture required by the wheat crop; hence alternate wheat–fallow is almost inevitably the standard practice. By sacrificing a crop, moisture is conserved from one season to the next, so that the

combined precipitation of two rainy seasons may suffice for producing one satisfactory crop. Fallow is considered essential for wheat production in the summer-rainfall areas of the middle latitudes when annual precipitation is less than 350–375 mm (Mathews, 1951).

Present yields of most non-legume crops grown continuously depend on the use of commercial fertilizers (Jackson et al., 1983).

Before the widespread use of N fertilizers, the advantages of fallow were greater in the cool (northern) than in the warm (southern) climates, a situation that appears to have changed in recent years. This is a clear indication that in the more humid parts of the region, the value of fallow lay mostly in increasing the N supply rather than in improving the moisture régime of the soil. Further proof is that in the more humid margins of the fallow–crop region, the advantages of fallow may be reduced or even eliminated by N fertilization, whilst in the low-rainfall areas, the advantages of fallow are generally increased through N applications.

Areas receiving 350–450 mm annual precipitation are transitional to annual cropping, and peas are grown in alternate years with occasional fallow periods (Dryland Agriculture Technical Committee, 1979). However, in the warmer Southern Great Plains of the USA, where ET in the summer is very high, the cereal–summer fallow is considered justified when the average annual precipitation is less than 550–600 mm (Loomis, 1983).

Fallow is effective in conserving soil moisture only if the amount, and, in particular, the distribution, of rainfall during the fallow period is such as to permit moisture penetration in depth. Practically all available moisture in the upper 20 cm of the soil will be lost by evaporation. Therefore, total seasonal rainfall must not only be sufficient, but individual rains must be sufficient to penetrate in depth. As losses by evaporation are confined mainly to the upper 10–20 cm of the soil surface, a far greater proportion of the total precipitation is lost from a relatively large number of light rains than from a smaller number of heavy rains. In an average season in southern Saskatchewan, less than ten showers contribute to water storage in fallowed fields from May to October. In a wet season, twice as many showers contribute, but in drought years the storage is almost nil (Staple, 1964). The relative water losses from a layer of fallow soil due to evaporation and drainage, respectively, are shown in Fig. 16.4.

Conditions for infiltration must be satisfactory, and run-off must be minimized by proper management practices. Moreover, the loss of stored moisture must be minimized by effective weed control.

The amount of water lost during the fallow period depends also on soil type. For example, under similar climatic conditions, in the Pacific Southwest, clay loam (fine, montmorillonitic, thermic Typic Chromoxererts) lost 35% less water by evaporation than did sandy loam (coarse-loamy, mixed, non-acid, thermic Typic Xerorthents) for 75 days after 20 mm of water was added to a soil that had been wetted to beyond

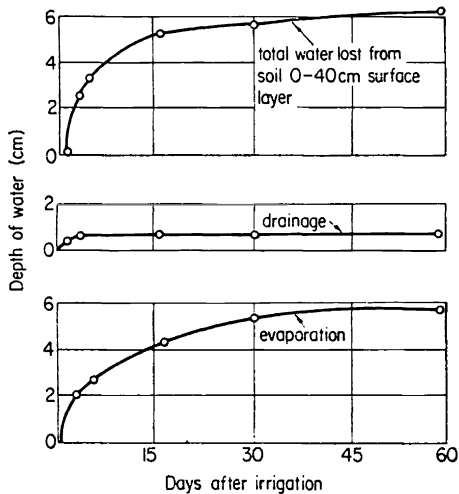


Fig. 16.4. Accumulated loss of water from a layer of fallow soil. The accumulated evaporation from this soil during the two summer months is shown on the lowest curve. The top curve shows the total depth of water leaving the 0–40 cm soil layer during the same period. The middle curve is the difference between the two former curves and represents downward drainage, which – as can be seen – is minimal in comparison with loss by evaporation. From Richards and Richards (1957). By courtesy of the US Department of Agriculture.

90 cm depth. The graphs are indicative of water losses to be expected under summer fallow in the winter-rainfall area of the Pacific Southwest (Luebs 1983) (Fig. 16.5).

Hinze and Smika (1983) describe the management practices of fallow:

- Fallow land should be weed-free from harvest to planting 14 months later. The wheat–fallow system encourages infestation by winter annual weeds, that have the same growth habits as winter wheat.
- Stubble should remain upright during as much of the fallow period as possible to trap snow in the winter and reduce evaporation during the rest of the year.
- More than 1.5 t/ha of straw mulch should be present at seeding.
- Large clods should be maintained during fallow and after sowing.

This procedure effectively increases soil water storage, provides nitrogen, assures better crop-seed germination and reduces wind erosion. However, even with the best management practices, summer fallow is not efficient in moisture storage, as the following examples demonstrate: in the Great Plains of North America, under an alternate crop–fallow system, the average amount of moisture conserved in the soil was only 16.3% of the total precipitation under conditions in which losses due to run-off and deep percolation were negligible and weeds were well controlled (Mathews and Army, 1960). For a rainfall of 400–450 mm this would amount to about 65 to 75 mm.

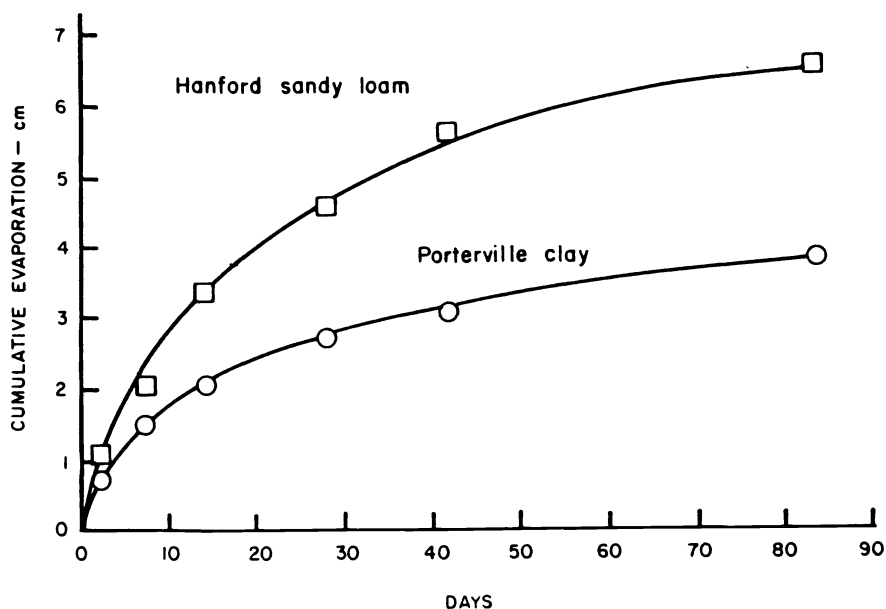


Fig. 16.5. Evaporative water losses from two contrasting soil types in the Pacific Southwest. From Luebs (1983). By permission of the American Society of Agronomy, Inc., the Crop Science Society of America, Inc. and the Soil Science Society of America, Inc.

However inefficient, summer fallow is effective: the additional water stored in the soil by fallowing may make the difference between success and complete failure of the succeeding crop in regions with marginal precipitation. Long-term weather records indicate that, in the southern high plains of the USA, a wheat–fallow rotation will produce yields in excess of 700 kg/ha in approximately eight summers out of ten, whilst with continuous cropping to wheat the odds of obtaining such yields are in only five seasons out of ten (Army et al., 1959).

In a study in Nebraska, comparing a fallow–wheat rotation with continuous winter wheat under semi-arid conditions, it was shown that fallow–wheat average yields were over three times as great as average continuous wheat yields. The fallow–wheat rotation also provided stable production with no crop failures, while continuous wheat failed to produce a crop in about one year out of three. Average water use efficiency for fallow–wheat was 80% greater than for continuous wheat, when annual precipitation was between 246 and 430 mm, indicating that the fallow–wheat was the more efficient of the two methods tested, in producing winter wheat with a rainfall of less than 430 mm. At least 580 mm rainfall was required in a summer-rainfall area for continuous wheat with nitrogen fertilizer to use water as efficiently as fallow–wheat without fertilizer. The nitrogen content of wheat grown on fallow was 0.22% higher than continuous wheat (Smika, 1970).

Ecofarming. While wheat–fallow is still the dominant cropping system in the Great Plains, a two crops in three years rotation has proven suitable for western Kansas and western Nebraska (Norwood et al. 1988).

Since 1971, a practice called *ecofarming* has been adopted, in which a cropping sequence of winter-wheat–summer-cereal (grain sorghum, maize or millet)–ecofallow is used.

Ecofarming is “a system for controlling weeds and conserving soil moisture in a crop rotation with a minimum disturbance of crop residue and soil” (Smika and Wicks, 1968). Ecofallow relies largely on herbicides for weed control, with a minimum of tillage operations.

Either minimum or no-tillage is practised throughout the rotation. In the former case, herbicides are applied after wheat harvest, and tillage as needed for weed control during fallow. The sorghum is planted directly into the residue of the winter wheat crop.

The summer crop disrupts certain insect cycles and facilitates the control of annual winter weeds. With ecofarming, four crops are produced every six years, whereas the traditional wheat–fallow rotation produces only three crops during this period. Risks from adverse climatic conditions are reduced, because not all the crops grow at the same time (Hinze and Smika, 1983).

The system is becoming widely adopted in areas receiving less than 500 mm; in Nebraska alone, ecofarming expanded in the period 1973–1981 from about 2000 ha to about 90 000 ha. A five-year study has shown that 46.75 mm of additional moisture was conserved during the wheat stubble period alone, increasing the yield of the subsequent maize crop by 15 to 25% (Meyer, 1983).

Flexible cropping systems. A model has been developed for cropping in a middle latitude region, which enables the farmer to assess the available soil water and expected growing season precipitation at seeding time before deciding on whether to grow a crop, what crop to grow or to leave the land fallow (Halverson and Kresge, 1982).

Jones and Johnson (1983) describe the following example of a flexible cropping system in use on the drier western edges of the region near the Texas–New Mexico state line, where wheat, sorghum and cotton are grown. Rotation between the crops is rarely fixed. If the cotton is damaged by sand storm or hail, sunflower is sown. On finer-textured soils, winter wheat is grown in a cotton or sorghum–fallow–wheat sequence. If soil moisture conditions are favourable in the fall after wheat harvest, wheat will be seeded again. If conditions are unsatisfactory, the land is fallowed and seeded to cotton or sorghum the following spring. When conditions are very favourable, the preferred crop is cotton, a high-value crop.

Various flexible cropping systems can be devised to suit different environmental conditions, especially in fringe areas.

Green manures. Long-term experiments have not shown any advantage in replacing fallow by green-manure crops in regions with less than 375 mm rainfall. Thus, in long-term experiments in Montana, where annual precipitation ranged from 290–375 mm, green-manure crops of sweet clover had no beneficial effects on dryland wheat yields (Army and Hide, 1959). The negative results may be ascribed to the kind of crop used for turning under (frequently a cereal), to the soil moisture depletion by the growing crop, to the drying out of the soil due to inversion when ploughing under the green manure, and, finally, to the decomposition of the mass of organic matter.

Green manures were found economically feasible for dryland cropping where at least 450–500 mm of rain can be expected (Army and Hide, 1959).

In trials in Nebraska, on a loess soil, a number of types of rotation were compared. The highest maize yields were obtained from rotations including two years of sweet clover (Duley, 1960). Oat and wheat yields were also increased in a legume rotation as compared with a non-legume rotation as indicated in Table 16.3.

In summary it may be said that a fallow–crop system, without soil-improving crops or practices, will reduce the organic matter content of the soil far more rapidly than does a continuous cropping system, and will eventually result in lower yields. The time required to reach this condition depends on the original level of soil fertility, the net quantity of nutrients removed annually, management practices (such as burning stubble, stubble-mulch farming, etc.), and the amount of precipitation.

In a cereal farming system, an increase of 100% in yield on fallowed land, to compensate for the loss of a cropping year, is not a precondition for making fallow economically justified. Stability of production, distribution of labour, and economy in weed control, may justify fallow even under conditions of lesser response.

Where precipitation is too low for successful crop production, fallow is indispensable. Where crops can be grown with a reasonable prospect of success, fallow is optional; its value is determined by other factors in addition to the degree of crop response, and the areas under fallow will vary from year to year – depending inter alia on economic factors and soil moisture conditions. It is therefore far easier to decide in which regions fallow is essential than where its use is optional.

Summer-rainfall regions in the low latitudes

In the semi-arid zone of Africa lying to the south of the Sahara, the two principal crops – sorghum and millets – are extensively grown on freshly cleared brush. They

TABLE 16.3

Effect of type of rotation on yields (kg/ha) of oats and wheat (Duley, 1960)

	Oats	Wheat
After two years of sweet clover	2175	4080
In a maize–oats–wheat rotation	1196	1842

have proven to be extremely sensitive to soil depletion in organic matter. After a relatively short period of continuous sorghum or millet, yields become too low even for primitive farming, and the land has to be abandoned.

The rapid degradation of the soil resulting from cereal monoculture is an almost irreversible process under the conditions of primitive agriculture employed in this region. The exhausted soil, abandoned by the farmer, is covered only sparsely with vegetation. The process of regeneration is delayed by overgrazing and brush fires, so that it takes many years to return to the original level of soil fertility.

Non-cropped fields are generally allowed to produce weeds, as a source of grazing and forage. Such weedy fallow rarely conserves moisture, and the following crop will often suffer from moisture stress. The weeds are an essential component in associated grazing systems (Power, 1990).

Non-cultivated fallow alternating with cereal production is therefore incapable of maintaining an acceptable level of production after brush clearing. The situation is no better when groundnuts, another important crop of the region, are sown continuously. Yields decline rapidly, and even mineral fertilizers are unable to maintain a satisfactory fertility level.

Alternating a groundnut crop with two or more years of fallow (non-cultivated) alleviates the situation without, however, providing a radical solution, as illustrated by the example given by Gillier (1960) in which yields of unshelled groundnuts on a depleted soil were only 355 kg/ha. After fallow periods of two, three, and six years, yields were increased by 24, 22, and 80%, respectively, still extremely low yields, even for subsistence farmers.

It is clear that simply alternating groundnuts with periods of fallow does not allow for the production of high yields. Even with mineral fertilizers, yields are increased by only 270 kg/ha. Further, the respite provided by fallow in the depletion process is very transitory: after two years of cropping, even following six successive years of fallow, the drop in yield is considerable.

It has been found that an alternation of crops is the first essential to maintaining a reasonable level of fertility. Short cycles of sorghum-groundnuts, with light doses of mineral fertilizers, alternating with fallow, have been found not only capable of maintaining the original level of soil fertility, but even of gradually increasing yields.

Thus alternation of crops, with short periods of cropping alternating with fallow periods of sufficient length, and the use of mineral fertilizers at moderate doses, have given the possibility of economic production within the framework of traditional agriculture of this region. But the inclusion of green manures in traditional farming has not been found to be justified.

In the semi-arid tropics of India, total seasonal rainfall is often in excess of the capacity of the soil to store water. In many deep-black soils (Vertisols), cultivated fallow is practised during the monsoon period, with cropping only during the post-monsoon period, on soil water stored in the root zone.

The reasons for not cropping during the rainy season include poor drainage; diffi-

culties in soil preparation, cultivation, and weed control; the risks resulting from the unpredictable onset of the rains; inadequate soil and crop technology. However, the consequences of leaving the soil bare during the rainy season are serious run-off and soil erosion (Krantz, 1981).

ICRISAT has developed an improved watershed-based system that allows both rainy-season and post-monsoon-season cropping on these Vertisols, in areas with adequate rainfall (cf. p. 715) (Stewart and Steiner, 1990).

Pulses

In the developing countries with a semi-arid tropical or subtropical climate, pulses form an important part of the diet and are included in most crop rotations, either in mixed cropping or as sole crops. These legumes remove a substantial portion of the N fixed, especially improved varieties with a high harvest index, which can remove more N in the grain than fixed during crop growth (Henzell and Vallis, 1977).

There may be exceptions to this general rule. Burford et al. (1989) point out that pigeonpea has a low harvest index – sometimes less than 0.20% for medium and late maturing varieties; the crop also sheds its senescing leaves from flowering onwards. The farmer removes the stalks, but these contain very little N. Sheldrake and Narayanan (1979) have calculated that the fallen leaves may contribute 40–60 kg/ha of N per year.

Mixed cropping

Concepts and definitions

Mixed cropping is a characteristic of traditional subsistence agriculture dating from antiquity. It is the rule in economies in which land, water, and capital are scarce resources limiting agricultural production and where cheap labour is plentiful (Palti, 1981). It is a method which attempts to make the most of the potentialities of the environment by planting, together or sequentially, two or more crops with different planting and harvesting times and growth habits.

Complementarity

Plants of the same species generally compete with each other more intensively than do plants of different species – mainly because of the latter's differences in plant architecture, root systems, and periods of maximum water requirements. In suitable combinations, different crop species can complement each other in making better use of environmental resources, mainly light, water, and nutrients.

Replacement intercropping systems are those in which each crop is sown at only a proportion of its sole crop population, and the total population is equal to the total

of its components. In *additive systems* each crop is sown at its normal population density, so that total populations are higher than in sole cropping (Willey, 1990).

A notable example of mixed cropping, practised by a primitive people, is the maize-beans-squash complex, which originated in Mexico during the period 1500–900 BC. It was so successful that it spread out from Mexico and became the basis of practically all prehistoric Indian agriculture in all parts of America.

The complex of three crops exploited the soil and the light energy most effectively: the beans climbed on the maize stalks, exposing their leaves to the light without excessive shading of the maize leaves; the squash grew prostrate on the ground and choked out weed growth. The mixed cropping also produced a highly balanced diet: the maize supplied most of the carbohydrates and certain amino-acids in which beans are deficient; the beans supplied the bulk of the protein, and also phosphorus, iron, and the vitamins riboflavin and nicotinic acid. The squashes added calories and an increment of fat (Stakman et al., 1967).

Intercropping is still practised on a large scale in the Mediterranean region, in Africa, and in India. In East Africa, it is exceptional of peasants to sow pure stands. Evans (1960) doubts whether it will be possible to introduce rotational systems of agriculture based on pure stands so long as the hoe is the main agricultural implement.

Efficient use of resources

Mixed cropping, in its various forms, has been shown to be more efficient in the capture and/or use of available resources than single-crop stands. Willey (1990) distinguishes between two basic ways in which mixed cropping can improve resource use: (a) by greater resource capture, and (b) by greater resource conversion efficiency, i.e., by more efficient use of a given unit of resource.

Use of light

By a proper choice of cultivars, planting time and spatial arrangements, it is possible to extend the time of full leaf spread, with maximum leaf area occurring for each crop when high solar energy is available, thereby increasing overall productivity potential (Sooksathan and Harwood, 1976).

Willey (1990) compared two widely used intercropping systems: millet-groundnut and sorghum-pigeonpea (Fig. 16.6).

In the millet-groundnut system, millet plants had much greater biomass, leaf area and light capture in intercropping than in sole cropping, but conversion efficiency was similar in both systems. The shaded groundnuts captured much less light in intercropping than in sole cropping, but their conversion efficiency was increased by 46%. The greater efficiency in light use of the groundnuts was ascribed to (a) the greater efficiency of the C3 canopy at low light intensities, and (b) the avoidance of light saturation of upper leaves. Overall, light capture was the same in both systems;

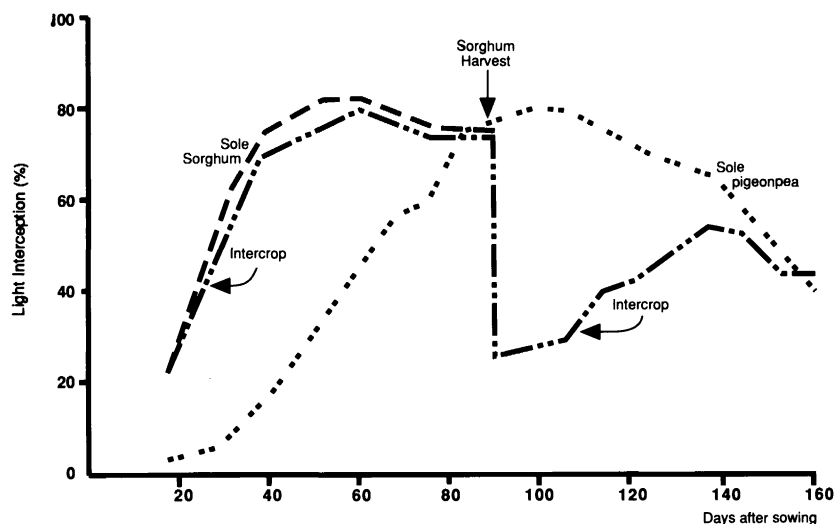


Fig. 16.6. Light interception in sorghum and pigeonpea sown as sole crops and as a 2-row sorghum : 1-row pigeonpea intercrop (means of three years). The figure illustrates the complementarity in the combination sorghum–pigeonpea as shown by the light interception patterns. Sorghum ensured good early interception of light and pigeonpea added some later interception; the total interception by the mixed crop was higher than in sole crops and the increase was directly proportional to the higher yields produced. From Willey (1990).

the erect canopy of the C4 millet used the light at the same efficiency as in sole cropping, whilst the C3 groundnuts were especially efficient at low light intensities.

In the sorghum–pigeonpea system, the early sorghum hybrid was much more competitive than the pigeonpea and its final yield was 95% of the sole crop. The slow early growth of the pigeonpea was suppressed by the sorghum and its final total dry-matter yield was only 53% of when grown alone. However, because only the early growth stage of the intercropped pigeonpea suffered from the competition of the sorghum, its harvest index was 36% higher than in sole cropping, and its final grain yield was 72% of the sole crop.

The sorghum ensured good early interception of light and the pigeonpea some later interception of light; together the two crops captured more light than in single cropping, and this was translated into higher yields because of the fuller use of light over time (temporal complementarity) (Fig. 16.7).

Water use

Intercropping can increase plant available water and its utilization by providing a greater canopy cover, which improves infiltration by protecting the soil from the impact of rain and increases the proportion of transpiration in evapotranspiration.

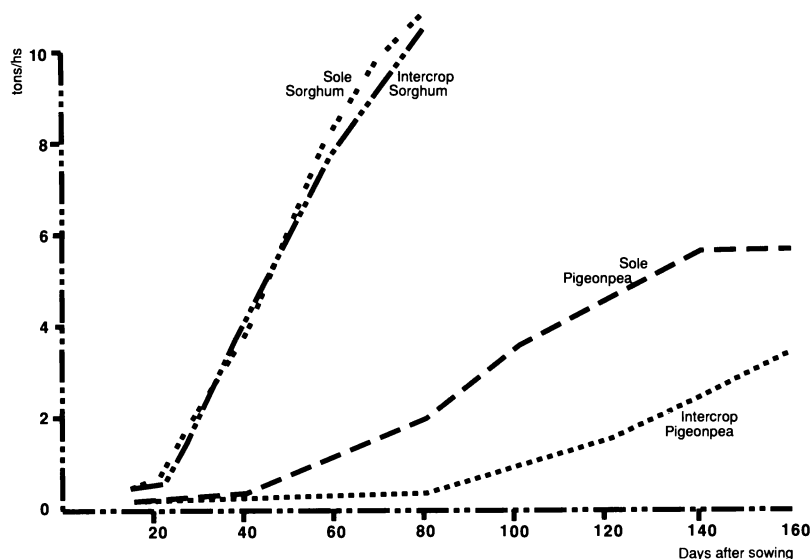


Fig. 16.7. Dry-matter accumulation in sorghum and pigeonpea sown as sole crops and as a 2-row sorghum : 1-row pigeon pea intercrop (means of three years). The growth patterns illustrated in the graphs show that sorghum was significantly the more competitive of the two crops and its dry matter accumulation was little affected by competition from pigeonpea. By contrast, the slow initial growth of pigeonpea was further depressed by competition from sorghum, resulting in a reduction of yield of over 50% of sole pigeonpea. From Willey (1990).

These effects are greatest when a rapidly established crop is grown with a crop with slower early development (Willey, 1990).

Various intercrop systems have been shown to capture more water than their sole crops, probably because the root systems of different crops explore different soil layers; an additional possibility is that temporal differences in rooting patterns may increase total water uptake for the intercropped system (Willey, 1990).

It was further found that the advantages of intercropping over sole cropping were even greater under poor moisture supply régimes, provided the total population of plants was the same in both systems, with each component in the mixed stand at a lower population density than when grown alone. The advantage of the mixed stand in this case is apparently due to each crop experiencing less competition in combination with another crop than when grown alone (so-called complementary resource use) (El-Swaify et al., 1984).

Staggered sowing of crops in overlapping periods can significantly improve water use efficiency in semi-arid areas. Crops requiring plenty of water, such as rice, are intersown with grain legumes which will grow during the rainy season, but will ma-

ture after the rains cease. Similarly, cotton can be sown into a stand of winter wheat, one to two months before the wheat will be harvested (Palti, 1981).

Nutrient supply

Many studies have shown greater nutrient uptake in mixed stands than in sole cropping; it is assumed that the same mechanisms favouring increased water uptake are involved: greater root concentrations or complementary exploration of the soil profile (Willey, 1990). In the long run, this can signify a more rapid exhaustion of soil nutrients, and the need for higher rates of fertilization.

There is evidence that the relative advantage of intercropping increases with increasing nutrient stress, though to a lesser degree than is the case for moisture stress. El-Swaify et al. (1984) suggest that intercropping systems may be especially beneficial under conditions when inherent fertility is low, and fertilizer application for rainfed cropping is negligible or nil.

In the case of legume–non-legume mixed cropping, there might be a possibility of nitrogen being transferred from the legume to the other crop. Willey (1990) points out that this contribution is easily overestimated. The nitrogen contribution from many intercropped legumes is generally limited, because the grain legumes grown remove most, if not all, the fixed N when their grain is harvested (cf. p. 757, 768).

Benefits from mixed cropping

Higher yields

A combination of improved capture of light, water and nutrients, and better utilization of these resources enables well-designed intercrops to yield 30 to 60% more than the individual crops (Syarifuddin et al., 1974). One of the important considerations is that this yield advantage can usually be achieved simply and without costly inputs (Willey, 1990).

This will be illustrated with a few examples from drought-prone areas in different dry regions of the world.

Intercropping maize or sorghum with groundnuts was found to give generally higher overall crop production per unit area than growing these crops singly. This was found to hold true in two areas of contrasting fertility as well as under conditions of contrasting rainfall, namely low, irregularly distributed rainfall versus favourable rainfall amounts and distribution.

Experiments at ICRISAT (El-Swaify et al., 1982) have shown that three typical Alfisol intercropping combinations, namely sorghum–pigeonpea, millet–groundnut, and pigeonpea–groundnut, yielded higher returns than when the crops were sown singly.

The advantage of the sorghum–pigeonpea intercropping, was the combination of an early, fast-growing crop, the sorghum, that ensures the use of early resources, and a later-maturing crop, the pigeonpea, that is least competitive during the growth and

development of the sorghum, and after the latter is harvested, takes fuller advantage of later resources. The millet–groundnut combination had the advantage of using light, water and nutrients more efficiently than each crop grown alone.

Improved yield stability

Improved stability of yields appears to be a major advantage of mixed cropping. In analyzing the data from 94 experiments on sorghum–pigeonpea intercropping, Rao and Willey (1980) found that for a particular ‘disaster’ level of monetary returns, sole pigeonpea would fail one year in five, sole sorghum one year in eight, but in the intercropping system, both would fail only one year in 36 (Fig. 16.8). Intercropping gave yield advantages and greater stability over a wide range of environmental conditions, and the authors found no evidence that these advantages were greater under stress conditions.

The improved yield stability is mainly due to reduced drought risks, and less damage by pests and diseases.

According to Rao and Singh (1990), the reduced risk from pigeonpea-based intercropping systems results from the combined effect of higher yields and reduced variability in yields; the superior yield stability of intercropping is especially high under low-input management. These authors, however, stress that the reduced risk from intercropping is not general, and depends on crop combination, cultivars and agro-

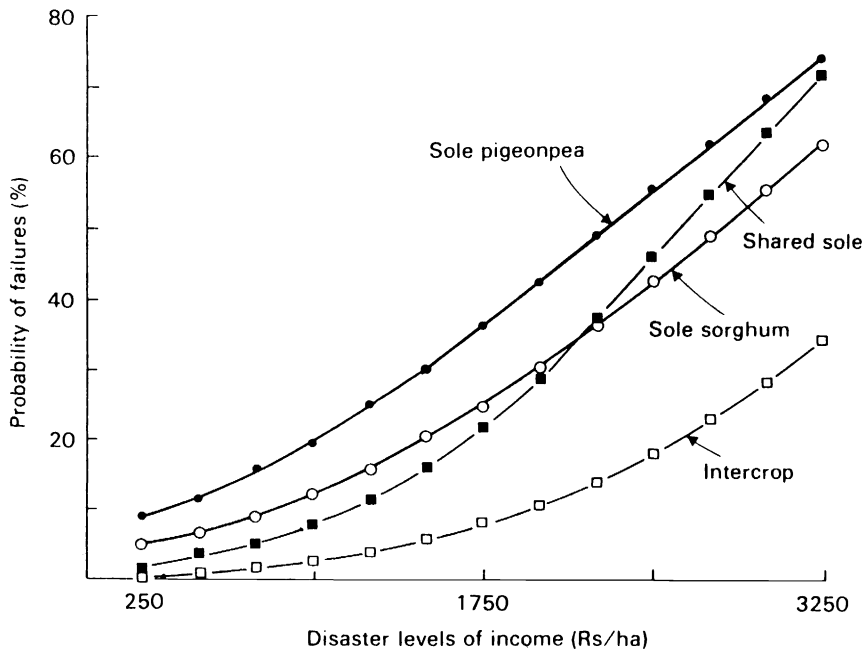


Fig. 16.8. Probability of failure for sorghum and pigeonpea in different cropping systems at given disaster levels of income. From Rao and Willey (1980). By permission of the Journal of Experimental Agriculture.

nomic management. For example, crops that mature at about the same time, such as sorghum/millet or millet/groundnut, compete more strongly with each other and intercropping therefore has less overall yield advantage over sole crops, and less yield stability than is the case with crop combinations in which the components have markedly different maturity times.

Reduced drought risks were found in maize–sorghum intercrops compared to single-crop stands (Cutie, 1975).

An interesting example of double insurance provided by mixed stands of sorghum and maize is described by Collinson (1972). In the 1940's, sorghum, mainly because of its drought resistance, was the preferred grain in many parts of Sukamaland. The variety widely grown was particularly susceptible to bird damage. As the bird problem increased, the sorghum was interplanted with maize, which is much less drought-resistant than sorghum, but is not attractive to birds. Tastes gradually changed, and as maize became the preferred grain, it was interplanted with sorghum as a drought insurance.

Crop mixtures of early and late varieties are sometimes sown by subsistence farmers – the former to provide insurance against early cessation of the rains, the latter to make possible higher yields when rainfall is abundant (Hall et al., 1979).

Reduced insect and disease damage: Mixed cropping has been shown to reduce the severity of disease and insect attack; it is assumed that one crop acts as a barrier to the spread of a pest or disease in the susceptible crop, or by producing a root exudate, acting against soil-borne diseases.

A few examples: cereal intercrops reduce insect attack on cowpeas in Africa and insect-borne diseases such as rosette and bud necrosis in groundnuts in India; sorghum was found to reduce soil-borne wilt disease in pigeonpea; in the Punjab it was found that cotton intercropped with beans (*Phaseolus aconitifolius*) was much less damaged by root rot (*Rhizoctonia* spp.) than when grown in a pure stand. Evans and Sreedharan (1962) reported that when castorbeans were attacked by mirids in mixed stands with groundnuts or soybeans, and their yield was reduced drastically, the associated crop gave a compensating yield increase.

In some cases, one component of the mixture serves as a trap crop protecting the other component(s). Occasionally, the trap crop also makes possible the maintenance or build-up of natural enemy populations. Hussey (1990) gives a few examples:

In India, damage to sorghum is reduced by 50 to 80% by intercropping with cowpeas. When cotton is interplanted with sesame, the latter attracts *Heliothis virescens* from the more valuable cotton crop and serves as a reservoir for natural enemies. In a maize–sorghum mixture, the maize-leaf aphid, *Rhopalosiphum maidis* serves as a food source for the ladybird *Hippodamia*, which subsequently moves to the sorghum, to feed on another aphid, *Schizaphis graminum*, at the time when the panicles of the sorghum emerge.

Adverse interactions have also been observed, when the two crops in the system have a pest in common: in the combination sorghum–pigeonpea, *Heliothis* pod-borer

attacks both crops and pod damage to pigeonpeas was found to be more severe in the mixture than when grown alone (Bhatnagar and Davies, 1981). In staggered sowing of crops, residues of one of the components may carry pathogens, such as *Ascochyta* spp. on pulse residues, or *Septoria tritici* on wheat stubble, able to survive the dry season (Palti, 1981).

Intercropping winter cereals (wheat, barley) with summer cereals (maize, sorghum) as practised in China, promotes the incidence of barley yellow dwarf virus and of *Fusarium graminearum*, which produces its Gibberella stage on wheat and maize, and then spreads by ascospores (Kelman and Cook, 1977).

Nutrient uptake and utilization

Nutrient uptake and utilization have been found to be more efficient in maize–rice and maize–soybean intercrops than in the monocultures of the respective crops.

Types of mixed cropping

In the semi-arid areas of India, in which annual rainfall is moderately favourable (>750 mm) and dependable, it has been shown that intercropping of a short- and a long-season crop, or sequential cropping of two short-season crops is possible (Virmani et al., 1989).

Willey et al. (1989) describe different types of mixed cropping that are appropriate for such situations.

Relay cropping

In relay cropping, a second crop is sown shortly before harvesting the first. The period of overlap is short, usually about two to three weeks: the second crop is sown when the first starts shedding its leaves, so that an increasing amount of light reaches the emerging crop. Because the period of interlap is short, and occurs when both crops make limited demands on resources, competition between the two components is minimal.

The advantages of relay cropping are: (a) the second crop is less likely to run out of moisture than in sequential cropping; (b) the establishment of the second crop is more assured, because the likelihood of catching end-of-season showers is greater and the first crop provides some protection against the ground drying out.

Intercropping

In intercropping, two or more crops are grown on the same area simultaneously. The crops may be grown in separate rows or in a random mixture. In this system, competition between the crops is maximized.

One of the most successful intercropping combinations has been cereal/pigeonpea, in a 2 : 1 row arrangement, with the populations of each crop the same as the recommended sole crop population. Both crops are dry-sown just before the beginning of

the rains; the cereal is harvested after about 100 days and the legume 100 days later, at the end of the post-rainy season.

Ratoon cropping

In ratoon cropping the stubble of a harvested crop is allowed to regrow to produce a second crop. This is possible only with a limited number of crops, such as sorghum and pigeonpea.

Ratoon cropping avoids the risks and costs of establishing a second crop. Early-maturing pigeonpeas appear to be a promising crop for ratooning. Yields are relatively high, if the pods of the second crop are picked without any cutting of the stems.

Sequential cropping

Sequential cropping is the growing of two consecutive crops, when the second is sown soon after the harvest of the first. The possibilities of sequential cropping in rainfed farming in the semi-arid regions have been increased as a result of earlier maturing varieties of the major crops, but are still limited to those areas in which precipitation is sufficient for a growing season of at least 180 days (>750 mm summer rainfall) (Willey, 1988).

Sequential cropping is practised successfully in the higher-rainfall monsoonal areas of India (>750 mm summer rainfall) on deep Vertisols; the first crop (maize, sorghum, or soybean) matures about the end of the rainy season, and the second crop (chickpea, safflower or sorghum) grows on residual water. The success of the second crop depends on the ability of the farmer to achieve a rapid turn-around between the two crops (Reddy and Willey, 1982).

Mixed cropping for modern agriculture

Shortcomings of mixed cropping

Modern agriculture, with very few exceptions, is based on pure stands. The exceptions are mainly forage and pasture crops, that can be sown and harvested simultaneously, or where the undersown legume is left after the cereal is harvested, and is then used for forage, grazing or green manure.

Weed control, whether mechanized or chemical, as well as pest and disease control, are hindered in mixed stands. Rational fertilizer applications to a mixture of different crops are difficult to plan.

The main limitation to mixed cropping in modern farming is that efficient mechanical harvesting of a mixed crop is generally not possible.

Willey et al. (1989) state that the key to alleviating these problems is to confine the different crops to separate rows. Seeding can easily be done mechanically in separate rows. Top-dressing fertilizers on the rows that need it is also possible. Even herbicides can be directed to specific rows, if this is needed. The major difficulty will continue to be harvesting.

In contrast to the guarded optimism expressed by the workers at several international research centres on the potential benefits of mixed cropping and the possibility of overcoming the limitations mentioned above, Loomis (1983) reaches completely negative conclusions regarding the desirability of mixed cropping in modern farming systems, with the exception of mixed stands of grasses and legumes in sown pastures. His major arguments are:

- The advantages of crop rotation for the control of disease, pests and weeds are lost.
- Timing of field operations, plant population, fertilization, method of harvesting cannot be optimal for each component of the mixture.
- The benefits of mixed cropping have been exaggerated. The common assumption that mixtures of different species complement each other by using different components of the environment, and that competition between plants of the same kind is more severe than that between different kinds is generally not the case for annual crops. Plant species compete for the same basic resources of light, CO₂, water and nutrients. If the competing species differ in traits (height, rate of growth), there will be winners and losers, and for the latter, competition between unlike kinds is more severe than in a pure stand.
- Water use may be less efficient. For example, relay cropping may require reduction in cover by the first crop to allow the second crop to be successfully established, thereby increasing losses of water through evaporation.
- Complementation of species with deep and shallow rooting cannot exceed in nutrient and moisture extraction a single species capable of exploring the entire profile.
- Mixing superior with less able species leads to a decline in community productivity. Whilst in a single species it is possible to maximize the photosynthetic rate of a full canopy of leaves arranged in an optimal way, this cannot be improved by including a species with inferior traits into the community.
- Regarding the claim for improved yield stability of mixtures, Loomis agrees that a mixture could be superior over a poor choice for monoculture, where climate is highly uncertain. However, under these conditions, a monoculture of an indeterminate species would be a better solution.

Loomis further contends, that in experiments on mixed cropping carried out to date, “either the mixtures or the comparison monocultures generally involve the same variety and the same low density as is necessary in the mixture, rather than optimum practices for monoculture”.

He concludes that good research, involving comparisons of mixed cropping versus diverse monocultures is required.

However, research workers are generally reluctant to undertake experiments on mixed cropping, partly because of the great number of possible combinations, but mainly because of preconceived ideas that no benefits are to be expected at advanced levels of farming (Andrews, 1972). As a result, it are mainly the international research centres that have undertaken this type of research and have developed improved

methods of mixed cropping, such as intercropping, relay cropping, etc., which mitigate, even if they do not eliminate, many of the drawbacks of the traditional methods. But even at these centres, the emphasis is, justifiably, on the improvement of traditional farming in developing countries and not the problems of modern agriculture.

Mixtures of cultivars of the same species

A modern alternative to mixed cropping is to blend several cultivars of the same species, in order to avoid excessive genetic homogeneity with its attendant disadvantages, such as the lack of ability to adjust to environmental variability, and the greater ease with which diseases and pests can spread in a genetically pure stand.

It is also postulated, that a judicious mixture of cultivars will allow various genotypes to complement each other and thereby improve yields. Still better results may be expected from varieties that have been bred specifically for intercropping and relay cropping (Loomis, 1983).

Multilines or composite varieties

Multilines are mixtures of strains derived from a series of crosses and backcrossed to a common parent. The objective of these mixtures is to blend strains with similar morphological characteristics, so as to minimize inter-strain competition, but with different genes for disease resistance in order to limit the spread of disease and the appearance of new pathogen mutants by preventing the rapid spread of inoculum from plant to plant.

Crop rotation under irrigation

Establishing a permanent crop rotation for irrigated crops is far more complicated than for rainfed crops, as the variety of different crops that can be grown is far greater. These can include grain crops, forage and pasture crops, industrial crops, and vegetable and ornamental crops, whose economic justification is far more subject to fluctuation than the cereal crops which form the backbone of the rainfed rotation.

Maintaining soil fertility and sanitation is far more difficult under irrigation than under rainfeeding, for reasons that have been discussed in Ch. 13.

Additional factors that have to be considered in establishing a crop rotation are the amounts of water available, their seasonal availability, their quality, and costs; the availability of labour and of specialized skills, the distance from markets, and many other local factors have also to be considered. For these reasons, whilst it was possible to define prototype crop rotations for rainfed crops in the semi-arid regions, this cannot be done for irrigated crop rotations in the arid areas. At most, certain basic requirements and desiderata can be outlined.

1. *Permanency and flexibility*

The rotation scheme must have permanency, and at the same time sufficient flexibility to allow for changes in the choice of crops when this becomes necessary as a result of fluctuations in the economic climate. This flexibility can be achieved by devising a crop rotation that is based not on a succession of crops, but on *groups* of crops with similar requirements and similar effects on the following crops.

2. *Periodic drying of the soil*

It is well known that a continuous succession of irrigated crops usually leads to a gradual decline in yield levels. Drying the soil at regular intervals is a most effective measure to counteract this tendency. Simply leaving the soil fallow is not a satisfactory solution as only the top soil dries out, leaving the lower layers moist for very long periods. An excellent solution is to include a cereal, particularly wheat, as the last crop to be sown in the rotation. The wheat in this case has a sanitary function to perform, as it does not share the root diseases of the principal intensive crops grown. The cereal enables a thorough drying out of the soil and a steep reduction in the number of pathogens. Deep tillage, after harvest, leaves the soil in huge clods, which are then baked by the sun for several months, during which time the rhizomes of perennial weeds are killed. The clods disintegrate with the first rains, thereby providing a well-aerated soil and excellent tilth.

One of the important characteristics distinguishing the arid and semi-arid soils from those in humid temperate regions, is that the former periodically dry out to a considerable depth. This is accompanied by a rise in soil temperature to 50–60°C (Aubert, 1962). This periodical drying out and heating of the soil has profound chemical, physical, and biological effects on soil fertility, which have some similarity to those ascribed to freezing in the colder and wetter regions. This is not surprising, as freezing is also a form of drying.

Exposing a ploughed soil to the effect of sun rays for prolonged periods is an age-old practice in arid lands, and is still in present-day use both in countries using traditional agricultural methods and in those using modern ones. The effect of drying and wetting on the soil structure depends on the type of soil, on the temperature of drying, on the degree of dryness achieved, and on the intensity of the wetting process.

Under natural conditions, drying affects mainly the upper soil layer to a depth of 20–30 cm. Drying the soil has a number of effects which may be considered under the headings of chemical, physical, and biological effects.

Chemical

The drying of the soil increases the availability of certain nutrients. Humus decompo-

sition, in a moist, warm, and well-aerated soil, proceeds at a slow, albeit steady, rate (Russell, 1961). If the soil is first dried and then moistened, the decomposition of the organic matter is considerably accelerated, releasing increased amounts of nitrogen. The more thoroughly the soil is dried, the higher the temperature at which it is dried, and the longer it is kept dry, the greater will be the subsequent nitrogen flush on decomposition (Birch, 1959). In arid or semi-arid areas, in which intervals between irrigations or rains may be fairly long and the temperatures high, the upper soil layer may dry out completely during these intervals. Under these conditions, when the soil is again wetted, considerable mineral nitrogen may be released. It is to the increased amounts of available nitrogen that Birch (1960) ascribes the principal beneficial effects of drying.

Physical

Drying the soil, with subsequent gradual rewetting, improves soil structure and is capable of restoring a soil structure that has been degraded by excessive compaction. Woodburn (1944) found that the summer exposure of a dense and impermeable clay to several cycles of drying and wetting by sun and rain, respectively, caused extensive aggregate development. The effects of alternate drying and wetting on soil structure were greater than those of repeated cycles of freezing and thawing. The exact mechanisms whereby extreme drying improves aggregate stability are not yet understood (Harris et al., 1966).

When soils dry gradually, they contract. This contraction is not uniform, and so cracks develop, sometimes to a considerable depth. The capacity of the soil to crack on drying depends mainly on its texture: the higher its content of soil colloids and the more uniform its texture is, the greater will be its tendency to crack on drying. The higher the content of colloids, the more the soil swells when wetted, and, consequently, the deeper the cracks become on drying. Adsorbed monovalent cations, especially sodium, have a similar effect (Vershinin et al., 1959). The formation of shrinkage cracks on drying was found to be more extensive in soils with a high proportion of montmorillonite clay than in illite clay (Buehrer and Deming, 1961).

Cracks fulfil a number of important functions (Hardy and Derraugh, 1947): (a) they facilitate penetration in depth of rain or irrigation water; (b) the alternate opening and closing of the cracks facilitates the incorporation of organic residues into the lower soil layers; (c) they facilitate the breaking up of the land; (d) they enable the deep penetration of roots into clay soils; (e) they are beneficial to drainage, which may be of paramount importance when it becomes necessary to flush excess salts out of the root zone; and (f) they help in drying the soil to a greater depth than would otherwise occur.

Soils in which deep cracks form are 'self-mulching': as a result of the action of wind, grazing animals, and gravity, the cracks fill up progressively with soil particles from the surface. This leads in the course of time to a mixing of surface soil and

subsoil, the effect being similar to that produced by burrowing animals and earth-worms in soils of the humid regions.

Biological

A distinct shift in the balance of the soil population, between saprophytes and pathogens, occurs frequently in irrigated soils where the combination of high temperature and favourable soil moisture frequently causes a proliferation of pathogens in the soil.

Drying the soil causes a marked reduction in the total number of micro-organisms. This action is, however, selective in the sense that it favours the saprophytes at the expense of many of the soil pathogens. Many of the beneficial saprophytes form resistant spores, which enable them to survive the period of drying and increase rapidly on rewetting, whilst many of the pathogens do not have this advantage, and are therefore destroyed.

Amongst the most resistant to drying are the nitrifying bacteria; this is one reason why soils that have dried out during the summer months, show an explosive activity in nitrification with the first autumn rains, as discussed above.

3. Maintaining soil fertility

In addition to the liberal use of chemical fertilizers, the turning under of organic manure, and green manures grown as catch crops, as well as the considerable amounts of residues that are produced by crops under irrigation, will enable the maintenance of a satisfactory level of fertility.

4. Long time intervals before sowing certain crops again

For some crops, such as sugar beets, that are very sensitive to certain diseases, a fairly long interval should be provided, before they are sown again in the same field.

5. Choosing the right sequence of crops

(a) The continuous sowing of grain crops (whether cereals or pulses) should be avoided as far as possible.

(b) Leguminous crops should not be sown one after the other, even when one crop is to be harvested for seed and the other for forage.

(c) Crops with common root diseases should not be sown in succession to each other.

(d) The best 'preceding crops' should be reserved for the most remunerative cash crops. Crops with the most favourable effects on the subsequent crops are, in order of merit:

- (1) perennial pastures, lucerne;
- (2) legumes for green manure, silage, silage, or hay; and
- (3) heavily manured vegetable crops.

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PART V

Crop Protection

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CHAPTER 17

Weeds and Their Control

Weeds and the damage they cause

Weeds have been defined in various ways, but the most appropriate definition for our purpose is: “a weed is a plant that in a given situation is more detrimental to agriculture than beneficial”. This definition takes into account that weeds under certain circumstances can also be beneficial: they provide grazing in areas that cannot be cultivated, or during periods when the land is not producing a crop, at the same time protecting the land against erosion; certain weeds may serve as food in periods of scarcity; while many weeds have important medicinal uses (King, 1966).

Competition for water

In dry climates, the deprivation of water to the cultivated crop is frequently the most damaging aspect of weed competition – both in the growing crop and in the fallow period between crops. It has been estimated that the amount of water saved by eliminating weeds in a maize field is equivalent to providing an entire irrigation at the time of maximum need (Mangelsdorf, 1966).

This conclusion has been confirmed by more recent findings: research in the central Great Plains, USA, a semi-arid summer-rainfall area, showed that weed growth produced 800 to 2700 kg/ha of dry matter after harvest; the resultant loss in soil water can reduce wheat yields by 500 to 1600 kg/ha of grain, and 1000 to 3200 kg/ha of straw (Greb, 1983).

Loss of yield

According to Wiese (1983), perennial weeds can reduce crop yields by as much as 75%. In various regions of the USA, annual weeds reduced maize yields by 13–85%, depending on weed species, weed populations, and crop growing conditions.

As an example of the economic impact of weeds, Nalewaja (1972) has calculated

that if wild oats were eliminated from cereal grains in North Dakota, the increase in wheat production would feed 13 million people on a diet of 2500 cal/day for one year.

Knake and Slife (1962) found that for maize and soybean infested with giant foxtail (*Setaria faberii*), the increase in dry matter produced by the weed was almost equal to the decreased dry-matter yield of the crop.

Competition from weeds begins to reduce future crop yields about four to six weeks after sowing, and continues to increase thereafter (Burnside, 1979) (Fig. 17.1) Krishnamoorthy et al. (1974) have shown that if weeds were not removed from pearl millet within 30 days from emergence, yields were reduced by 70%.

Costs of production

Estimates indicate that 50 to 75% of all tillage operations are done solely to control weeds (Burnside, 1979).

Weeds increase harvesting costs of cereals and other crops by increasing fuel requirements and equipment wear; by slowing cylinder speed and thus preventing proper threshing; and prevent proper separation of weed seeds from crop seeds (Burnside, 1979). They require costly cleaning of seeds, reduce water flow in irrigation and drainage channels, and increase fire hazards.

Toxicity and health problems

Poisonous weeds can contaminate food. For example, darnel (*Lolium temulentum*), is a weed that is widely associated with wheat; flour prepared from grain contaminated with 0.5% darnel seeds is toxic (King, 1966).

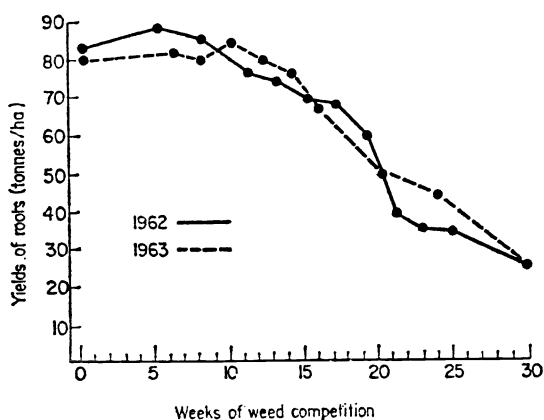


Fig. 17.1. Effect of weed competition on yields of irrigated sugar beet. The yields of roots are from plots in which weeds grew uncontrolled within the rows for different periods after spring planting. From Dawson (1965). By permission of the American Society of Sugar Beet Technologists.

Allergenic weeds cause disease by the inhalation of pollen, affecting millions of people and resulting in the loss of numerous workdays. Other weeds cause skin irritations in various degrees of severity.

Weeds host vectors of various diseases; elimination of weeds in perennial crops in California has resulted in the complete control of eye gnats which serve as vectors for tropical ulcer and mastitis (Burnside, 1979). Aquatic weeds harbour mosquitoes. The elimination of brush is essential to free areas in Africa from the tsetse fly, the vector of sleeping sickness.

Many weeds in pastures are poisonous to stock; a notorious example is *Halogeton glomeratas* in the semi-arid rangelands of the USA.

Hosts for crop pests and pathogens

Many pathogens and pests affect hundreds of plant species and attack both cultivated plants and weeds and can be transmitted from the one to the other. Consequently, weeds are frequently major factors in the epidemic spread of pathogens, virus diseases and pests (Gerechter-Amitai, 1973).

Palti (1981) groups the pathogens for which weeds serve as diffusion agents as follows:

- Vector-borne diseases, many of which can be seed borne, such as pea seed-borne mosaic, with *Vicia villosa* as a host.
- Obligate, air-borne fungal pathogens; probably the best known example is the role of common barberry (*Berberis vulgaris*) as an alternative host to stem rust (*Puccinia graminis*) of wheat, which enables the build-up and dissemination of enormous amounts of inoculum.
- Facultative air-borne fungal pathogens, such as *Botrytis cinerea* (which has thousands of hosts), *Alternaria* spp., *Stemphyllium* spp., or *Rhizopus* spp.
- Soil-borne pathogens, such as *Sclerotium rolfsii* and *Sclerotinia sclerotiorum* which have a wide range of hosts. Systemic invasion through the roots enables aerial dispersal. Resistant pathogen structures, such as sclerotia and chlamydospores are frequently released from weed roots into the soil. Many weeds are symptomless carriers of soil-borne fungi, such as *Fusarium* spp. and *Verticillium album*. Included in this group are nematodes such as *Meloidogyne javanica*, *M. incognita*, and *M. hapla*, each with over 500 host species.

The same weed species can be an active agent in the spread of various categories of diseases. Johnson grass (*Sorghum halepense*), for example, serves as the source of numerous major diseases of maize and sorghum: four smuts, several leaf spots, and, most important, the dwarf mosaic and chlorotic dwarf viruses of maize (Palti, 1981).

In semi-arid areas, weeds in irrigated fields and their borders can carry pathogens or insect vectors of virus diseases through rainless summers. Many grasses help rusts

through the summer and attack rain-fed winter cereals early in their growth (Gerechter-Amitai, 1973).

Many insects live on weeds during certain stages of their development. Grasshoppers winter and increase in weedy areas, and move on to crops during the growing season. Hundreds of weed species harbour nematodes, which parasitize crop plants. Solanaceous weeds, for example, harbour the golden nematode of potatoes. Weeds also provide habitats for rodents (Burnside, 1979).

Quality of agricultural produce

Weeds such as *Allium* spp. taint the dairy produce of grazing cattle; wool and hides contaminated with burrs, seeds and awns of weeds have a lower market value. Other weeds, cause damage to the mouths or udders of grazing animals. Many weeds cause digestive disturbances and weight loss of grazing livestock.

Survival characteristics and competitive ability

Weeds are naturally endowed with a number of characteristics which increase their survival rate and their ability to compete with crop plants. Their vitality frequently helps them to overcome the ill effects of herbicides. They produce enormous quantities of seeds. In many species the seeds germinate only when conditions favourable to the survival of the seedlings are assured. In others, the seeds have various periods of dormancy: only a fraction of the total quantity of seeds germinates at a given time, so that seed reserves are always available in the soil, even if one or more generations are destroyed by natural causes or by the efforts of the cultivator.

Dispersal mechanisms

Weed seeds often have structural or chemical characteristics that facilitate their natural spread. Very small seeds can be carried along by winds, together with dust particles. Other weeds have seeds borne in burrs, with spines, rough-coated seed pods or covered with sticky exudates which enable them to become attached to animals and be transported to other locations. Palatable weed seeds can be transported for long distances by birds or other animals and are excreted without losing their germination ability.

Farmers are frequently responsible in the first place for causing the weed infestation of their fields. The most obvious way in which weeds are introduced is by the use of contaminated seed supplies. Hence, the importance of seed laws to safeguard the farmer against unscrupulous or negligent seed suppliers, and of seed certification schemes to ensure proper supervision of seed production and distribution.

The use of manure, especially that of sheep that have grazed in weedy areas, unless properly decomposed, can contribute enormous amounts of seeds to the fields.

The introduction of combine harvesting has also favoured the spread of weed

seeds. In the past, cereals were harvested by hand or by binders and thrashing was concentrated in a single place, so that weed seeds could be collected and destroyed. Nowadays, however, the combine harvester does a preliminary cleaning job, separates a large proportion of weed seeds, and scatters them in the field behind the combine.

Irrigation and drainage ditchbanks, uncultivated patches, fence rows, weedy banks of roadsides, and country lanes, are also permanent sources of weed re-infestation.

Inappropriate tillage methods may help to divide and disperse the roots and rhizomes of perennial weeds. Delays in tillage, in mowing, or in the harvesting of crops, may provide the weeds with an additional opportunity to disperse their seeds. Controlling the weeds in one crop, and neglecting weed control in the next, gives a new start to weed infestation. It is estimated that if only 1% of a typical stand of weeds survive control methods, it is capable of producing over 100 million new weed seeds per hectare (Day, 1966).

Kinds of weeds

Weeds, encompassing an enormous variety of species, can be classified in a number of ways. With the advent of selective weed killers, the most purposeful grouping of weeds is probably into two main groups: narrow-leaved weeds and broad-leaved weeds.

Narrow-leaved weeds

Narrow-leaved weeds are generally monocotyledons, and include Gramineae, Cyperaceae, and Juncaceae. This group includes annuals and perennials. The annuals are particularly troublesome in cereal production, because the similar characteristics of weed and crop make selective control very difficult. *Avena sterilis*, *Phalaris paradoxa*, and *Lolium temulentum*, in cool-season crops, and *Setaria* spp. and *Panicum* spp., in warm-season crops, are examples of this group. Among the narrow-leaved perennials are some of the most ubiquitous weeds of the warm arid and semi-arid regions: bermuda grass (*Cynodon dactylon*), johnson grass (*Sorghum halepense*), and nutgrasses (*Cyperus* spp.). Their competition with the cultivated crop, mainly for water, is severe in dry habitats. However, it is only when the land is put under irrigation that the potentialities of the perennial weeds to compete with and depress the cultivated crop become fully apparent – hence the need for their eradication as the first step before irrigation is started.

Broad-leaved weeds

Most of the annual weeds of the arid regions have a life cycle adjusted to seasonal

precipitation, and include ephemerals whose life cycle is completed within a few weeks. However, the most pernicious annual weeds are those whose life cycle has become adjusted to that of an annual crop, germinating together with the crop – their most depressing effect being in retarding the development of the young seedlings. They benefit from any practices carried out for the benefit of the cultivated crop, and scatter their seeds before or at the time of harvesting the crop.

In the dry regions there are many types of xeric weeds, such as thistles and related plants.

Woody plants

A large number of woody plants, including many shrubs and trees, are detrimental mainly in the grazing lands of the arid regions, where they compete strongly with more palatable and nutritious forage plants. A characteristic example is the group of mesquites (*Prosopis* spp.).

Parasitic weeds

The dodders (*Cuscuta* spp.) are a widely distributed genus, capable of both sexual and vegetative reproduction, and parasitizing a large number of crop plants.

Broomrapes (*Orobanch* spp.) are fairly widespread in semi-arid regions of the world. They are damaging mainly to a few crops, including certain legumes, vegetables and tobacco.

Witchweeds (*Striga* spp.) are restricted to the hotter arid regions, in which they parasitize mainly the summer cereals, including maize, sorghum, sudan grass and rice. The plants produce enormous numbers of extremely minute seeds.

Seeds of witchweeds will only germinate when they lie close to the roots of susceptible plants that can serve as hosts. The roots exude a chemical which triggers the germination of the seeds of the parasite (Klingman, 1979).

Aquatic weeds

Reservoirs, canals and open distribution systems that are rich in nutrients, invariably become invaded by aquatic weeds, and, if not well maintained, eventually become choked by their dense growth. Control of the weeds may be extremely expensive (White, 1977).

Aquatic weeds reduce water flow, cause silt deposition, and consume water. It is estimated that in the arid and semi-arid areas of the USA, aquatic weeds use water quantities that would be sufficient to irrigate about 130 000 to over 300 000 ha annually (Burnside, 1979).

The construction of the Aswan Dam was followed by infestation of the Nile and associated irrigation systems by aquatic weeds. Previously, the annual flood used to

wash away most of the aquatic growth, especially floating weeds. After the floods stopped, the water hyacinth became a serious problem (Imam, 1977).

Aquatic plants harbour the snail vectors of certain diseases of man and livestock; the aggravation of schistosomiasis almost invariably follows the establishment of irrigation projects in tropical areas. They also provide shady resting places for disease-carrying mosquitoes (White, 1977).

Aquatic plants may also confer some benefits; some provide food for fish and shelter for fish fry; submerged plants contribute to the aeration of the water. The benefits are, however, generally outweighed by the undesirable effects (White, 1977).

Annual and perennial weeds

Weeds can also be classified according to their persistence.

Seedlings of *annual weeds* usually have vigorous growth which gives them an advantage when grown with crop plants; this, coupled with the enormous numbers of seed germinating at one time, provides strong competition to crop plants (Klingman, 1979).

Most of the *perennial weeds* do not compete with annual winter crop plants but are usually found in undisturbed sites in non-cropland and in perennial crops, such as pastures, lucerne, and orchards. It are the relatively few perennial weeds that spread by strong rhizome or stolons and aggressive lateral roots that are the most aggressive weeds of crops, and the most difficult to eradicate. Widespread in dry regions are: canadian thistle (*Cirsium arvense*), nutsedge (*Cyperus* spp.), field bindweed (*Convolvulus arvensis*), johnson grass (*Sorghum halepense*), bermuda grass (*Cynodon dactylon*) and quackgrass (*Agropyron repens*).

When irrigation is introduced, these weeds become a major problem. Perennial weeds do not depend for their competitive ability on very rapid seedling growth or overwhelming numbers of seed. They are highly competitive after establishment because of their ability to survive tillage operations and to recover rapidly by using the food reserves stored in their roots and rhizomes for their subsequent rapid spring growth and spread (Klingman, 1979).

Weed control

Stages of development

Efficient weed control implies a knowledge of the lifecycle of the different weed species and of their special characteristics. Their rate of growth differs at different stages of development, and their vulnerability to weed control measures varies accordingly. Plants are most vulnerable to herbicides during periods of rapid growth, and after they have depleted their food reserves (Åberg, 1964).

The effects of weed competition are mainly felt in the young crop; the much more rapid rate of growth of both the aerial parts and the roots of many weeds give them a considerable advantage in depressing and even crowding out the crop plants among which they are growing.

From the point of view of weed control, three stages are of significance:

(a) *Seedling stage*. The young plants are weak, their root system is not yet developed, and their total leaf area is limited. This is an ideal stage for weed control; mechanical methods such as harrowing, disking and cultivating, are especially efficient and economical during this period.

Selective control is especially effective only if the weeds are at this stage, whilst the cultivated plants are already more developed. Or alternatively, the weed seedlings can be selectively destroyed before the crop plant has emerged above the soil surface.

(b) *Vegetative stage*. The growth rate is accelerated in the vegetative stage, the leaf area increases rapidly, and the root system is already extensive. This stage is not favourable for mechanical control, as even uprooted weeds are frequently capable of re-establishing themselves under favourable weather conditions.

The large and actively growing leaf area increases the lethal effect of herbicides but, in order to be effective, high rates are required, which may cause excessive damage to the cultivated crops. Recovery of the crop may be hastened by fertilization, in particular with nitrogenous fertilizers. In some cases, e.g. with certain thistles such as *Cirsium arvense*, the most appropriate time for spraying with auxin herbicides is immediately before flowering, as at this time the amount of reserve carbohydrate is at its lowest level (Åberg, 1964).

(c) *Reproductive stage*. Growth practically ceases in most weed species in the reproductive stage, and the assimilatory activity of the leaves decreases. This is generally not a favourable stage for effective weed control. However, the apparent absence of damage to the plant by late spraying cannot be the only criterion: the chemical may be transferred to the seeds, and become active when the seeds germinate, causing damage to the seedlings (Åberg, 1964).

Spraying at the time of flowering may cause many abnormalities in crop plants, e.g. in maize, where flower malformations may be induced, with a resultant reduction in grain yield (Åberg, 1964).

Methods of weed control

In the course of centuries, a number of mechanical, ecological, biological, and chemical methods of weed control have evolved. Weeds are, however, so aggressive, persistent, and ubiquitous, that if control is to be effective, all available methods have to be integrated into a planned programme of continuous, long-range efforts to reduce the weed population. It is therefore not surprising that weed control involves some of the highest costs in crop production (Ennis et al., 1963).

In recent years, there has been a retreat from the unbridled use of herbicides in semi-arid agriculture. As in other areas of plant protection, the tendency is to adopt integrated control, by combining mechanical and chemical methods, thereby reducing costs and damage to the environment (Yudelma and Hillel, 1988).

Whilst most weed control measures are the responsibility of the individual farmer, communal efforts are frequently essential, because a successful control or eradication campaign must include non-agricultural land, rights of way, ditches, urban and industrial areas. Occasionally, legislation may be required to ensure that all agencies involved, including the farmer, comply with instructions; a case in point is the campaign carried out against the common barberry, as a major means of controlling the spread of cereal stem rusts.

Mechanical control

Even with the effective modern chemical methods available, mechanical methods of weed control are still frequently justified, as they may be less expensive and less dangerous to neighbouring crops or orchards. However, even intensive cultivations, planned for effective weed control, cannot destroy in a single year more than about 50% of the viable seeds. It is estimated that a ten-year control programme will reduce a typical weed seed population of 500 millions per hectare, to about half a million (Day, 1966).

Hoeing and hand weeding

Hoeing and hand weeding still form a considerable and inevitable part of the human effort involved in primitive agriculture. Hand weeding rice was found effective in increasing yields by 45% (IRRI, 1966).

Even with the most modern methods of weed control, individual weeds or patches of weeds are apt to escape unscathed, and it is then usually justified to hoe or pull them – either because of their direct effect on the crop, as they impede mechanical harvest, or in order to eliminate a source of re-infestation.

Tillage

Even after the advent of chemical weed killers, tillage methods are still, for many situations, the most effective and economical means of weed control.

It is estimated that in the USA, from a half to three-quarters of all tillage operations are done solely to control weeds (Burnside, 1979). Ploughing, cultivating and harrowing, make possible weed control before sowing the crop, and there are appropriate tools that can do a satisfactory job even after its emergence. The younger and smaller the weeds are, the more efficient and economical will be their control.

The role of tillage in weed control consists of:

- (a) provoking the germination of weed seeds, which can then be easily destroyed by mechanical or chemical means;
- (b) bringing roots or stolons to the surface, where they will dry out under the sun;
- (c) repeated cultivation, thereby depleting the food reserves of the plant; and
- (d) uprooting or smothering the weeds with soil.

The tillage may consist in cultivating a field between cropping periods (clean tillage), in passing through a sown field with special equipment that destroys the weeds without severely damaging the crop (blind tillage, accomplished by harrows, rotary hoes, finger weeders, etc.), or in intertillage of row-crops.

The disturbance of the soil surface stimulates many weeds to germinate (Klingman, 1979). Therefore, the first tillage operation usually stimulates the re-appearance of a new wave of weeds, and needs to be followed by a second operation for their destruction. The implement chosen should be the one that under the given circumstances – soil condition, weed size, age of crop, etc. – will destroy weeds efficiently at the least cost to the farmer. Tillage operations should be as superficial as possible, and adjusted to the minimum depth needed for effective weed control. Deeper tillage is more expensive, brings a new supply of weed seeds to the surface, and in intertillage damages the roots of the cultivated crop unnecessarily.

A special method for controlling deep-rooted perennial weeds is repeated cultivation at regular intervals, over a period of one or more years, until all underground buds have been destroyed. This is achieved by consistently preventing top growth, so that the root reserves are exhausted and the weed is starved. However, the underground parts of hardy perennial weeds contain enormous food reserves, enabling them to survive frequent cultivations for years (Day, 1966). The method is therefore time consuming, expensive, and has an unfavourable effect on soil structure. Any let-up in cultivations, or even a single excessively long interval between cultivations, may undo all the previous work. With the advent of chemical herbicides, it is doubtful whether this laborious method is justified, except under exceptional circumstances.

Tillage combined with irrigation

One of the most effective means of weed control is a pre-irrigation, before sowing, with a quantity of water sufficient to wet the soil to the full depth of the future root system. Then cultivating the field superficially before or during sowing (if a combined tillage and sowing operation is carried out) will destroy the weeds that have germinated following irrigation. The seeds of the crop are sown in moist soil at a depth that is sufficient to ensure germination without additional irrigation.

The surface soil dries out, effectively preventing germination of additional weeds until the next irrigation. In view of the earlier irrigation in depth, this next irrigation can be delayed for two months and more after sowing, so that the crop is well advanced when the next wave of weeds appears, making selective control easy.

Mowing

Mowing annual weeds at flowering time is a method of preventing seed propagation rather than an efficient method of weed eradication. Frequent and regular mowings of perennial weeds exhaust the food reserves of the underground storage organs, weaken the plants, and may occasionally lead to their death when environmental conditions become unfavourable. A similar effect is achieved by frequent and close grazing.

Mowing is most effective against erect, tall-growing plants, and least effective against low, prostrate plants that produce their seed near to the ground (Jordan and Shaner, 1979).

Ecological methods

Crop competition

Some crops, such as rank-growing forage crops, are able to compete successfully with weeds; their inclusion in the crop rotation will help to weaken if not to eliminate certain weed types, especially if the weeds start active growth at a time when the cultivated crop is already well developed (for example, *Cynodon dactylon* in a winter cereal). The choice of crop varieties, such as commercial hybrids, that have high seed viability, rapid germination, early emergence, seedling vigour, and rapid growth, also contributes to weed control. Weeds that have been weakened by competition are the more easily killed by selective herbicides. On the other hand, varieties with little vegetative development, such as the new dwarf varieties of wheat, are more susceptible to weed competition than are the leafy, high-growing varieties that they are replacing.

One of the traditional methods used for combating weeds was sowing a thick stand of the crop. Heavy seed rates gave the crop a distinct competitive advantage over the weed population in the field. However in dry regions, where a relatively low plant population is one of the major means of adjustment to a limited soil moisture supply, this method of weed control was self-defeating. On the other hand, if low sowing rates were used, the additional space was taken up by weeds, again defeating the farmer's purpose. With the advent of selective herbicides, this dilemma has been generally resolved.

Smothering

Flooding. Flooding as a means of weed control is frequently used in rice production. Generally it is inefficient in achieving full control with other crops, as many weed seeds can withstand flooding for long periods, and the method is extremely wasteful of water. Undesirable effects on the soil and on raising the water table may also result.

Mulches. Thick mulches of straw or compost, and, more recently, dark-coloured plastic mulches, can smother perennial weeds and prevent the germination of annual weeds. These methods are expensive, and usually are justified only on relatively limited areas for high-return crops.

Fire

Fire already served Palaeolithic Man to clear away unwanted growth, stimulate annual plants, and aid in food collecting. Burning is a method of improving production of grass in many primitive economies, and in modern range management controlled burning is an important tool for controlling brush in rangelands; it is also usually the first essential step in range reseeding and general improvement. The burning usually has to be followed by the application of herbicides to control resprouting from the stumps and prevent the development of new seedlings. Burning in preparation for tilling and planting is accepted practice in many agricultural economies (Sauer, 1952).

Woody plants that are of inferior value for grazing, may become established in grasslands which are not submitted to burning. In the Great Plains of North America, the cessation of burning has contributed to the conversion of millions of hectares into mesquite jungles.

Flame cultivation

In connection with what may be termed 'flame cultivation', it may be noted that in cotton, for example, the stalk hardens much earlier than do the stems of the weeds that infest the crop. This makes it possible to find an appropriate time when a flame will destroy the weeds selectively, without harming the cotton. The operation depends for its success on the weeds being very small and much less developed than the cotton plants. The cotton plants should be at least 15–20 cm high and the stem 5 mm thick (Tupper and Matthews, 1962). The 'flame-weeder' has to be well adjusted, and the proper speed used, for the flaming to be effective.

The burning destroys only young weeds; after each irrigation or rainfall, a new 'wave' of weeds appears. Flaming can be repeated a number of times, 3–5 days after irrigation, until the appearance of the first bolls.

The use of flame cultivation in cotton was widespread in the 1960's and has since declined following the steep increase in the cost of butane and the advent of effective herbicides for cotton (Wiese and Chandler, 1979).

Crop rotation

A succession of different crops facilitates weed control. Certain weeds are almost obligatory associates of specific crop plants, and if these are sown continuously, effective weed control may become impossible.

For example, *Lolium temulentum* (darnel) is found in all cereal grain samples in deposits of carbonized plants, and is also found in abundance in ancient Egyptian

grain (Helbaeck, 1958). To this day, it infests wheat crops in temperate and in semi-arid regions. It is most difficult to separate the seeds of the weed from the cereal grains, and control in the growing crop is also extremely difficult.

Weeds whose growth and propagation is favoured by a certain crop may be weakened or checked by an appropriate succeeding crop. Leguminous crops for hay, grown during the rainy season, with their favourable nitrogen and moisture régime, encourage the rapid spread of perennial weeds such as bermuda grass (*Cynodon dactylon*). Conversely, if the following crop is a closely sown cereal, competition for nitrogen, moisture, and light, will greatly weaken the grass, which may be further damaged by close grazing of the stubble. Annual weeds which thrive in the winter cereal are easily destroyed during a winter fallow preceding the summer crop. Many other examples could be given.

Crops that are more competitive for light than the weeds can be included in the crop sequence; these are called smother crops, and can serve as precedents for less competitive crops.

In farming systems using mixed cropping (cf. p. 768) the appropriate choice of the components of the crop mix can provide effective weed control. Litsinger and Moody (1976) give the following examples: in the Philippines, mung beans, grown as an intercrop with maize, reduce weed growth; in Nigeria, cowpeas sown during the first weeding of cereals, develop a canopy of leaves that smother additional waves of germinating weeds, and make further weeding unnecessary.

Solarization

Covering the moist soil with transparent plastic sheets traps solar radiation, thereby heating the top soil to temperatures exceeding 50°C. This method has been developed mainly for disease and nematode control in areas with strong solar radiation and for high-value crops (Katan, 1980) (cf. Ch. 19); it is however also effective in killing most seeds of annual crops in the treated layer.

Horowitz (1991) reports good residual control of most annual weeds achieved after temperature maxima at 5 cm depth exceeded 45°C for ten days, and the effectiveness of the control increased with the duration of the treatment. Soil moisture was essential to sensitize the seeds to high temperature.

Hard annual seeds and perennials with established underground systems apparently escaped damage by solarization.

It is also possible to achieve efficient control in bands, with narrow sheets of 20 to 50 cm width.

Biological control

The biological control of weeds requires a more cautious approach than is the case for insect pests. Most effective biological control agents are not native to the areas in which they are to be used, and there must be assurance that they will not attack

related species of crop plants. Experience and research have shown that a marked reduction in one species of weeds in a cultivated crop results in a parallel increase in another weed species (Tschirley, 1979).

Insects, mites, plant pathogens, and aquatic and terrestrial herbivores have been used as biotic agents in weed control (Watson, 1989).

Biological control has been most successful in native pastures, where even a small impact on certain noxious weeds can increase forage yields (Wiese and Chandler, 1979). Because of the great diversity of annual and perennial species in pastures, there is little likelihood that control of one aggressive weed will result in its replacement by an equally aggressive and noxious weed.

Weed-eating insects

Biological control of weeds by insects has had a few spectacular successes: in Australia the control of cactus (*Opuntia* spp., which by 1925 had infested 24 million hectares), by the moth *Cactoblastis cactorum*, is probably the best known. Klamath-weed or st. john's wort (*Hypericum perforatum*), an introduction from Europe which infests the ranges in the arid west of the United States, has been controlled by a beetle (*Chrysolina gemellata*). The beetle destroys the foliage, thereby impairing the ability of the plant to maintain the extensive root system that is essential for surviving summer drought (Huffaker, 1957).

Weeds introduced from foreign countries have frequently been the most difficult to control by conventional means, and have been the most susceptible to biological control, by an insect which is also an alien (Huffaker, 1957).

The reason for the limited scope for biological control by insects is its serious potential danger. The need to find an insect that is specific in its choice of host – so that crop plants are not endangered by introducing the new pest – is imperative. The introduced insect must have considerable adaptability to a new environment, so that it can multiply rapidly and control the weed effectively.

A more recent approach, 'augmentive' or 'inundative control', for the biological control of native or introduced weeds, of annual crops grown in monoculture, consists of "mass propagation and periodic release of exotic or natural enemies that may multiply during the growing season but are not expected to become a permanent part of the ecosystem" (Batra, 1982).

Bioherbicides

The use of plant pathogens, mainly fungi, for weed control is becoming increasingly prevalent (Watson, 1989). A bioherbicide (or mycoherbicide) is "a preparation of living inoculum of a plant pathogen, formulated and applied in a manner analogous to that of a chemical herbicide in an effort to control or suppress the growth of a weed species" (Watson, 1989).

According to Templeton et al. (1986), bioherbicides have the greatest potential for

the control of weeds that have been resistant to chemical control, for crop mimics and for parasitic weeds.

The desired characteristics of a potential bioherbicide include: growth and sporulation in artificial media; high virulence; genetic stability; restricted host range; broad tolerance range; prolific propagule production; ecologically innocuous (Templeton et al., 1979).

From a review of the potentials of bioherbicides for effective weed control, Watson (1989) concludes that "bioherbicides should not be viewed as alternatives to chemical herbicides, but rather as complementary tactics in intergrated weed management systems".

Two endemic pathogens have been registered in the USA for weed control: *Colletotrichum gloeosporioides* for the control of northern jointvetch (*Aeschynomene virginica*) in rice and soybean, and *Phytophthora palmivora* for the control of stranglervine (*Morrenia odorata*) in citrus. Techniques have been developed for testing the virulence, producing the inoculum, and field application of these 'mycoherbicides', and are already in commercial use (Watson, 1989).

Allelopathy

A new promising approach to biological control is the study of toxins excreted by the roots of certain crop plants that inhibit or prevent growth of weeds (Tschirley, 1979).

Until recently, most research interest has been directed toward the harmful effects of allelopathic weeds, such as canada thistle and quackgrass, on crops. Presently, the allelopathic characteristics of crops that could suppress growth of nearby weeds is being studied. Oats, grain sorghum, cucumbers, wheat, have been found to be detrimental to certain weed species. The most frequently encountered form of crop allelopathy is the release of an allelochemical from the decaying residues of the crop, which inhibits growth of certain weeds in the next crop. Unfortunately, some crops are also sensitive to these allelochemicals (Banks, 1984).

Biocontrol of aquatic weeds

Another promising field is biocontrol of aquatic weeds (Tschirley, 1979). The nutria (*Myopotamus coypu*), a large South American rodent, was introduced accidentally into Lake Naivasha in Kenya, and within two years the rodents had completely eliminated the dense growth of water-lilies (cf. p. 425). This unplanned success was followed by equally unpredicted harm to birds and other fauna, which constitute an important tourist attraction, and are dependent on sufficient vegetation in the lake (Mitchell, 1977).

Catch crops and trap crops

These are used for the control of parasitic weeds, such as witchweeds. A catch crop that is a host to the parasite is sown and ploughed under before the parasite produces

seeds. A crop plant that is not host to the parasite, but induces it to germinate, is called a trap crop.

Legumes can serve as trap crops for witchweed, a parasitic plant of maize. Seeds germinate on the roots of the legumes, but are unable to complete their lifecycle and die (Kommendahl and Windels, 1979).

Chemical control

Early control methods

Chemicals for selective weed control have been in use since the end of the nineteenth century. Solutions of copper and iron salts, ammonium sulphate, potassium salts, and diluted sulphuric acid, have been used for destroying broad-leaved weeds in cereals. Kainite and calcium cyanamide dusts were also used for this purpose. These are all caustic herbicides, which burn the tissues of plants. The most widely used before the advent of the new hormonal weedkillers, was the nitrophenol DNOC (called sinox in the USA), introduced in 1932. The selective action of all these herbicides is due mainly to morphological differences between the cereals and the broad-leaved weeds that are destroyed.

Organic herbicides

The inorganic compounds were either corrosive and hazardous to handle, effective only at high volumes or very expensive. As the limitations of these substances became more obvious, and the escalating cost of labour became more limiting, the chemical industries in a few countries began large-scale testing of organic compounds. These have a major advantage: if a compound was found to be effective, extensive series of related compounds could be synthesized and could be modified to adapt them to specified functions (Elliott, 1980); they are also relatively cheap, and can be easily applied, requiring less water than inorganic salts (Robinson, 1980).

The development of the selective organic herbicides is one of the most significant advances in agriculture of the 20th century. A whole array of new techniques and chemicals have provided the farmer with means for selective control of weeds in most crops, even including those that were considered to be most susceptible to the hormonal herbicides.

Absorption of herbicides by the plant

Herbicides penetrate into plants mainly through the leaves or roots.

Foliar absorption. The herbicides may act by *contact* or by *translocation*. In the former case, the foliage is killed, whilst in the latter case the herbicide moves throughout the plant, reaching young growing points and moving down to the roots. The herbicides may penetrate the leaves partly through the stomata, but usually do so mainly through the cuticle. Stomatal penetration would enable rapid penetration by

the herbicides, but is relatively ineffective in the hot and dry regions of irrigation agriculture because of stomatal closure and rapid drying of the spray (Crafts, 1964).

Whilst the herbicide salts are polar*, their acids, esters, etc, are non-polar, and will therefore tend to be absorbed more rapidly through the leaf cuticle, which is composed of non-polar materials. The absorption of the polar herbicides is improved by the addition of wetting agents, which may thereby increase the herbicide's toxicity considerably (Staniforth and Loomis, 1949), but at the same time may reduce its selectivity (Klingman, 1961). Absorption rates of herbicides are increased by high temperatures, and within biologically supportable limits the rate is doubled with each increase of 10°C (ibid.).

Absorption through the roots. Herbicides can be applied to the surface of the soil and then incorporated into the upper soil layer by a light cultivation, by rain or by irrigation. They may also be injected below the soil surface. The chemicals are absorbed by the roots, polar herbicides being more rapidly absorbed than non-polar herbicides. However, non-polar substances may be converted in the soil quite rapidly into polar substances: e.g., the non-polar 2,4-D ester may be converted successively into the 2,4-D acid and then into a 2,4-D salt.

Some herbicides, such as EPTC, oxadiazon, and proflam, though applied to the soil, are capable of penetrating the plant through the hypocotyl. As the plants develop, they become less susceptible to soil-applied herbicides, and foliar application becomes the preferred method. Other herbicides, such as the dinitroanilines, are only partially translocated to the shoots; their major effect is to delay root development (Horowitz, 1989).

Absorption by germinating seeds. No herbicide has yet been developed that can kill dormant weed seeds (Horowitz, 1989). A chemical that could induce dormant weed seeds to germinate, would be an important tool for weed control. This would make it possible to overcome the problem of delayed germination, whereby weed survival is ensured in spite of control measures taken during the life of a crop.

Various herbicides from among the thiocarbamates and dinitroanilines are absorbed by germinating weed seeds and kill the emerging seedling (Horowitz, 1989).

Translocation of herbicides through the plant

Herbicides that are absorbed by the leaves are translocated in the phloem towards

*'Polar' ions or molecules have regions that are 'electrically positive' and regions that are 'electrically negative'. Non-polar molecules do not possess strongly positive and strongly negative areas within the molecule. Most organic substances are non-polar. Polar compounds (such as most herbicidal salts) tend to be soluble in polar solvents (such as water) and insoluble in non-polar solvents, such as oils and most organic solvents (Klingman, 1961).

other parts of the plant, moving in the general direction of the roots. If the herbicide is too toxic, as for example when it is applied at an excessive rate, the phloem is killed, thereby obstructing the translocation of the herbicide throughout the plant and reducing its effectiveness. Even if the top of the plant dies, the roots may still remain unaffected and growth may subsequently be renewed from underground buds, etc.

By contrast, herbicides that are absorbed through the roots are transported upwards through the xylem, together with plant nutrients, in the transpiration stream. As the xylem consists mainly of non-living tissue, it is not damaged by toxic substances. Translocation from the leaves may also occur downwards, through the xylem, in plants that are suffering from a water deficit (Kennedy and Crafts, 1927).

Glyphosate, in particular, is rapidly translocated through the plant to the root system, and is therefore especially effective for the control of perennial grasses (Horowitz, 1989).

Kinds of herbicides

The number and variety of herbicides has increased enormously in recent years; some disappear after a relatively short period of use, to be replaced by other, more effective compounds. New compounds are being added to the recommended list. Approximately 150 herbicides are currently registered and used.

It is interesting to note that a relatively large number of the earliest herbicides to be developed are still being used, have not been superseded, and are commercially viable (Makepeace, 1980).

For various reasons, among them the expansion of no-tillage and reduced tillage methods, which are heavily dependent on herbicides, it is expected that herbicide use will continue to increase in the future. Because of inflation and stricter regulation, it is, however, becoming more expensive and increasingly difficult to develop new herbicides (Wiese and Chandler, 1979).

Herbicides in current use can be classified in a number of ways:

(a) Their effect on plants: by *contact*: which kill only those parts of the plant which are exposed to the chemical (e.g., paraquat, diquat, dinoseb); or *translocated*, i.e., when they are applied to one part of the plant they are carried to other parts of the plant by plant tissues (2,4-D, glyphosate).

(b) Their way of uptake: through the *foliage* (bentazon, glyphosate); through the *roots* (diuron, trifluralin); or both (atrazine).

(c) Mode of action: *selective*: kill or damage groups of weeds without significant harm to the cultivated crop (2,4-D on cereals, diuron on cotton); or *non-selective*: kill or damage most plants indiscriminately (e.g., amitrole, glyphosate, paraquat).

(d) Persistence in soil: *non-persistent* (paraquat); *short-* (2,4-D); *medium-* (prometryn, oxadiazon); or *long-persistent* (diuron, simazine).

Soil sterilants kill or cause long-term damage to plants when applied to the soil,

and are used for roadsides, industrial areas, etc. (e.g., bromacil, monuron, picloram, tebuthiuron).

It is not within the scope of this book to present a full account of all the herbicides that have so far been developed and are currently in use; only the most important groups of compounds involved, their mode of action, and some of the principal herbicides will be described here.

Herbicidal oils

Diesel oils and discarded lubricating oils have been used for general weed control on waste ground. Light distillates, with a medium boiling range and containing about 25% of unsaturated and aromatic hydrocarbons, are used for selective control of weeds in umbelliferous crops, which have an inherent resistance to these oils (King, 1966). The selective action of these oils is based on their damaging the cellular membranes in susceptible plants, whilst those of resistant plants are not damaged (Ashton et al., 1961). These oils are, however, bulky and relatively expensive, while they frequently taint the crop with an oily taste.

Spot treatment of weeds with oil and lateral oiling of cotton were widespread practices in the 1960's. Weed control with oil has since decreased as a result of the steep rise in the cost of oils and labour, and the availability of effective chemical herbicides (Wiese and Chandler, 1979).

Phenols

Nitrophenols were the first organic chemicals to be used for selective weed control. As early as 1932, the sodium salt of 2-methyl-4,6-dinitrophenol became widely used in agriculture under the trade names of DNOC (Europe) and sinox (USA) (Brian, 1964).

The toxic effect of the phenol herbicides appears to be due to the prevention of the generation of adenosine triphosphate (ATP, needed for all biological activities that require energy), thereby preventing growth (Van Overbeek, 1964).

Auxin-type growth regulating herbicides

Certain synthetic auxins have the same general physiological action as the natural plant auxin 3-indoleacetic acid (IAA) on cell elongation in shoot tissue, but are not rapidly inactivated in plant tissues by the enzyme that destroys IAA.

Chlorinated phenoxyalkanoic acids

The chlorinated phenoxyalkanoic acids constitute one of the most important classes of herbicides, historically and economically. They are derivatives of aliphatic carboxylic acids, such as acetic acid.

Phenoxy compounds

At certain concentrations, substituted phenoxy acetic acids can act as selective herbi-

cides; they were the first and still are the most widely used hormonal weed killers. The best known are: 2,4-dichlorophenoxyacetic acid (2,4-D); 2-methyl 4-chlorophenoxyacetic acid (MCPA); and 2,4,5-trichlorophenoxyacetic acid (2,4,5-T).

2,4,5-T was found to be very recalcitrant to biological degrading. In spite of its efficacy for brush eradication, it has been removed from most markets as undesirable, due to dioxin contamination and its effects on man (Lynch, 1983).

The phenoxy compounds are quickly absorbed and translocated throughout the plant both through the leaves and through the roots; sensitive plants may react within 10–12 h after being sprayed. Though death may occur only weeks later, the weeds cease to compete with the crop plant shortly after being sprayed. The affected individuals show typical symptoms: grotesque, prostrate plants with malformed leaves and twisted stems. These are the result of disorganized cell division and deranged metabolic processes; they appear to be caused by an excess production of RNA that is induced by the 2,4-D and results in hormonal imbalance (Van Overbeek, 1964).

The phenoxy compounds are rapidly broken down by soil micro-organisms, so that there is no significant danger of build-up to toxic levels in the soil.

The s-triazines

The s-triazines were discovered in 1952, and soon became widely used. They affect the Hill reaction, and hence photosynthesis, leading to the starvation of the plant (Moreland et al., 1959).

Atrazine was the most widely used herbicide of this group. It served predominantly as a selective herbicide for broad-leaved and grassy weeds in maize and sorghum, but found applications in many other crops, and as a general herbicide. Because of its relative water solubility, atrazine was effective under relatively dry conditions (Birk and Roadhouse, 1962). This characteristic was subsequently found to be the greatest drawback of this herbicide: it leached easily into the aquifer and was the most frequently detected herbicide in groundwater. For this reason, its use in California, for example, has been prohibited.

A number of other s-triazine herbicides have been developed, with different toxicity spectrums, such as dipropetryn, metribuzin, prometryn, terbutryn (Horowitz, 1989).

Substituted amides

There are two major groups of amide herbicides based, respectively, on substituted anilines, and chloroacetamide (Plimmer, 1979).

Propanil is commonly used on weeds in rice, which is able to convert the herbicide to a less phytotoxic compound. Naptalam is used to control germinating seedlings of many grasses and broad-leaved weeds. Propyzamide is used in fruit trees, various vegetables, and ornamentals (Makepeace, 1980).

The chloroacetamides serve mainly as pre-emergence herbicides in a number of crops; they are toxic at very low concentrations to the germinating seeds of a large

number of weeds, especially grassy weeds. They are, however, effective only in the earliest stages of germination, by inhibiting cell division in the root tip (Van Overbeek, 1964).

The best known herbicides of the chloroacetamide group are CDAA and CDEA; they control grassy weeds in many crops. They are rapidly degraded in the soil.

Carbamates and thiocarbamates

Carbamate herbicides interfere with the normal process of cell division in a way similar to that of colchicine. Plant roots are particularly susceptible and are rapidly killed (Crafts, 1961). For this reason, these herbicides are mainly applied through the soil.

Propham and chlorpropham are used for the control of many annual grasses. The volatility of propham limits its usefulness, and it must be incorporated at shallow soil depths to retain its activity (Plimmer, 1979).

Thiocarbamates are bound in dry soils, but are relatively volatile in wet soils.

Eptam is used as a pre-emergence herbicide against grassy weeds and for the control of *Cyperus rotundus*. The chemical breaks down in moist soil, producing toxic vapours that penetrate plant roots.

Substituted ureas

The urea herbicides are closely related to the amides and anilines. Wilting is the first symptom of the toxicity of these compounds. Monuron or CMU and diuron or DCMU are extremely toxic at low concentrations, which is an important characteristic for soil-applied herbicides. Both monuron and diuron were used for selective pre-emergence treatments, and as general herbicides, mainly against annual dicotyledons. They are rapidly taken up by the roots, transported to all parts of the plant and interfere with photosynthesis by inactivating chlorophyll. Both compounds are broken down in the soil by microbial activity.

Other herbicides of this group include: chloroxuron, linuron, and methabenzthiazuron (Horowitz, 1989). Monuron and benzthiazuron are no longer approved for use.

Nitroanilines

Nitroanilines are characterized by their bright red colour and very low solubility. Trifluralin affects seed germination and growth of weeds. It is relatively volatile and easily degraded by light, and must be incorporated into the soil. A number of similar compounds have been developed as herbicides (Plimmer, 1979). These include: benfluralin, dinitramine, ethalfluralin, isopropalin, and pendimethalin (Horowitz, 1989).

Bipyridils

A large number of bipyridilium compounds have been tested in recent years, of which two, diquat (1,1-ethylene-2,2-dipyridilium dibromide) and paraquat (1,1-dimethyl-

4,4-dipyridilium dichloride), have proven to be the most effective. The two are very similar in their biological properties, but diquat is somewhat more toxic to broad-leaved weeds, as paraquat is to grassy weeds (Brian, 1964).

The bipyridils are contact herbicides, that at very low concentrations kill weeds within a few hours after spraying, and are especially active under conditions of bright sunlight. They are rapidly absorbed and translocated to all parts of the plant, killing and drying the leaves. In contact with the soil, they are rapidly adsorbed by the soil colloids and inactivated, so that there is no danger of toxic residues from them.

The bipyridils can be sprayed on small weed seedlings that appear before a susceptible crop emerges above the soil. The crop will not be adversely affected, as the herbicide will have become inactivated by the soil before the crop emerges.

It has been found that diquat effectively controls a dodder, *Cuscuta trifolii*, which is a major parasitic weed of lucerne in the Mediterranean region (Boon, 1965).

The bipyridils are very toxic and accidental ingestion can be fatal.

Aliphatic acids

Several chlorinated aliphatic acids have proven to be of great value in the control of grasses (Plimmer, 1979).

The sodium salt of trichloroacetic acid (TCA) is used in a number of crops as a pre-emergence herbicide for the control of grassy weeds. It is fairly persistent in dry soil, but breaks down rapidly in moist, warm soils. It is very water soluble, and is therefore easily leached from the surface layer of the soil. TCA is broken down by resistant species, whilst it accumulates in susceptible species.

Dalapon (2,2-dichloropropionic acid) is a strong acid that persists in the plant for weeks without undergoing any breakdown. It is slow-acting, has no acute toxic action, has little effect on the growth of the roots, but inhibits growth of the stem apex. Its action appears to be due to the breakdown of proteins into toxic products. Possibly, selectivity is due to differences between plant species in detoxifying the breakdown products resulting from the action of the herbicide (Van Overbeek, 1964).

Among the newer compounds, acrolein is used to control aquatic weeds, and glyphosate is used for general control of annual weeds (Plimmer, 1979).

New herbicides

Notwithstanding the limitations mentioned above, several groups of herbicides have been added in recent years. Others, such as DNOC, sinox, IPC, CIPC, TCA, and simazine, have become redundant as they are replaced by more effective, more selective, cheaper, and/or more environmental-friendly compounds.

At present, every major crop can be protected by a selective weed programme (Barrons, 1979). Progressive farmers keep informed of current developments through professional journals and by seeking advice from extension officers.

Among the newer groups of herbicides of importance are (Horowitz, 1989):

Sulfonyl ureas: chlorimuron (soybean); chlorsulfuron (small grains); metsulfuron

(small grains, woody species); sulfometuron (non-crop areas); thifensulfuron (cereals).

Imidazolinones: imazaquin (soybean, groundnut); imazapyr (soil sterilant); imazethapyr (soybean and other legumes).

Of particular importance are a number of selective herbicides for the control of noxious perennials, such as *Cynodon dactylon* and *Sorghum halepense*, that are tolerated by broad-leaved crop plants. These include dichlofop, fluazifop, haloxyfop, quizalofop, and sethoxydim.

Mixtures

No single herbicide can give complete control; various 'cocktails' of herbicides have been developed for specific situations in different crops. The herbicide industry has introduced wide-spectrum herbicide mixtures that give good results on almost all weeds the farmer is likely to encounter (Makepeace, 1980). There are, however, incompatible herbicides that cannot be mixed together. For example, dichlofop-methyl, widely used in cereals, is incompatible with most herbicides for broad-leaved weeds (Horowitz, 1989).

Mixtures have the additional advantage of preventing, or at least delaying, the appearance of resistance by reducing the doses of the most resistance inducing herbicides (cf. p. 822) (Gressel, 1987).

Herbicide synergists make possible lower rates of herbicide application.

Trends

The trend is toward highly active herbicides that are environmentally safe. With these new ultralow-rate products, a few g/ha of active material control a broad spectrum of weeds. For example, a new sulfonylurea post-emergence grass herbicide for maize is applied foliarly at rates of 35–70 g/ha and does not require moisture to activate (Everhart, 1990).

Selectivity of herbicides

The selective action of herbicides is based on characteristics of the herbicide or the way it is applied, in combination with differences between specific morphological and physiological characteristics of the crop plant involved and the weeds it is desired to control. Selectivity is not absolute, the degree of selectivity depending on the dosage, the formulation, the method of application, environmental conditions, and the stage of plant growth (Day, 1966).

Morphological basis of selectivity

The vital meristems of broad-leaved plants are located at the tips of the shoots and in leaf axils, and are therefore relatively exposed to the action of herbicides. By

contrast, the growing points of cereals are located at the base of the plant and are protected by the leaf sheath. Occasionally they are even situated below the soil's surface.

Cereal leaves have a waxy cuticle that is finely corrugated, so that there is no intimate contact between the toxic herbicide and the leaf epidermis. The leaves are also narrow and more or less erect, so that the amounts of herbicide that come in contact with leaves are relatively small.

Broad-leaved weeds, as their name implies, have wide foliar surfaces and horizontal leaves that absorb large amounts of herbicide; the epidermis is smooth, so that the spray spreads in a thin film and is in intimate contact with the epidermis.

Differences in the thickness of the cuticle influence the amounts of herbicide absorbed by the leaves; plants with thick cuticles will be less susceptible to a herbicide than those with thinner cuticles. The number, size, and location of stomata vary for different plant species. As the stomata are one of the means of entry of the herbicide into the leaf, it follows that the differences in stomata between species will affect their relative susceptibility to herbicides.

The emergent stem of the plant is not easily wettable in most species; it also loosens the soil as the seedling emerges, so that effective contact with the herbicide in solution is minimal (Hartley, 1964). This is one reason for the absence of damage to the emerging seedlings of the crop plants, as they pass through the soil layer in which soil-applied herbicides are concentrated, whilst the weed seedlings germinate in the upper soil layer in which the herbicide is concentrated, and absorb the chemical through their roots.

Physiological basis of selectivity

Not all the mechanisms of the selectivity of action of herbicides have been elucidated. Differences in soil permeability, in metabolism, in the enzyme system, and in polarity, may be involved. By affecting one or more of these systems, certain essential biochemical processes may be hindered or overstimulated, causing imbalance or dislocation of vital processes in the plant.

The simplest selective mechanism is in operation when a physical or biochemical process prevents the translocation of a herbicide in one species, giving it an advantage over plants in which the chemical is rapidly translocated to all parts of the plant. Alternatively, resistant plants metabolize the compound into an inactive form more rapidly than do sensitive plants.

2,4-D reacts with plant tissue substrate to form 2,4-D protein complexes, which have no toxic effects. In 2,4-D-resistant plants, the rate of formation of these complexes is very rapid, whilst it is slow in 2,4-D-susceptible plants (Butts and Fang, 1956).

Different enzyme systems may be involved in different plants, resulting in selectivity of herbicides. For example, certain weeds produce enzymes that convert homologues of 2,4-D such as 2-(2,4-DB) or butaxone [4-(2,4-dichlorophenoxy) butyric

acid], which have no herbicidal activity, into 2,4-D to which the weeds succumb, whilst other plants such as lucerne do not have this mechanism and so remain unaffected.

The opposite process is exemplified by the effect of simazine, a very potent herbicide, which is absorbed by maize without ill effect; the maize plant has a detoxification mechanism that hydrolyzes the simazine into an inoffensive substance.

Methods of application

Methods of application have been devised which ensure that the weeds will be contacted by the herbicide, whilst only minimal amounts reach the crop plants.

The sprays may be directed below the crop's foliage, so that only the stems of the crop plant are wetted, whilst the foliage of the weeds absorbs most of the application. Special shields may be used, which protect the crop plant from the spray.

Herbicides in granular form will roll off the crop's foliage and reach the soil. Rain or irrigation will move the herbicide superficially into the soil, where it will be absorbed by the shallow roots of the weeds.

In pre-emergence application, the location of the herbicide nearer to the site of the germinating weeds than to the seeds of the crop plant ensures the killing of the former, with a minimum of damage to the latter.

A variation of this method can be used for transplanting vegetable seedlings or field crops. A suitable herbicide, such as oxadiazon, is sprayed onto the soil surface. The herbicide, which remains immobilized in the upper soil surface layer, is absorbed by the emerging weeds. Sensitive crops can then be transplanted without harm, provided the roots are placed below the treated layer and contact with treated soil is avoided.

An interesting method of controlling the parasitic weed broomrape (*Orobancha* spp.), is to spray a suitable general weed killer, such as glyphosate, on the host plants at a dose too low to harm them, but which is lethal for the parasite that absorbs the herbicide from the host plants (Horowitz, 1989).

For sensitive crops for which no satisfactory selective weed control method has been found, the problem may be solved if more progress is made with herbicide protectants and antidotes. These will also possibly contribute to overcome the very difficult problems of freeing crops from closely related wild species (Robinson, 1980).

An improvement in selectivity can be achieved by coating the seed with a material such as activated carbon that adsorbs the herbicide, or alternatively, by placing a layer of absorbant material just above the seed row (Ripper, 1956).

Pre-sowing treatments

Pre-sowing treatments may be applied to kill weeds that have emerged after seedbed preparation has been completed, when actual sowing has been delayed, for example,

because of weather conditions. By spraying with an appropriate herbicide, the need for additional tillage operations can be avoided.

The principal application of pre-sowing treatments in semi-arid regions is their use for controlling weeds during the fallow period between crops – the so-called chemical fallow. Their great advantage is in the possibility of controlling weeds in the early stages, or even in preventing their emergence. Tillage is too dependent on weather and soil conditions to be as effective as chemical weed control in this respect.

The mechanical incorporation of the herbicide into the soil may have as objectives:

(a) *Placement of the herbicide for maximum effectiveness.* The optimal depth in this case will depend mainly on the site of uptake of the herbicide, e.g., the triazines are mainly absorbed through the roots, many carbamates are taken up through the coleoptiles of gramineous plants, and EPTC penetrates through the bulblets of nut-grass (*Cyperus rotundus*). In the last case, it was found that incorporation by disking had the additional advantage of tearing the chains of dormant bulblets and inducing their germination (Horowitz, 1965).

(b) *Protecting herbicides against loss by volatilization and photodecomposition.* A very thin protecting cover of soil is usually sufficient to achieve this aim (Hartley, 1964).

Pre-emergence treatments

The herbicide is sprayed on the soil surface at the time of sowing or shortly after, and so is concentrated in the very shallow soil layer in which the seeds of most annuals germinate. The seeds of the crop are planted at a lower depth; the crop may have

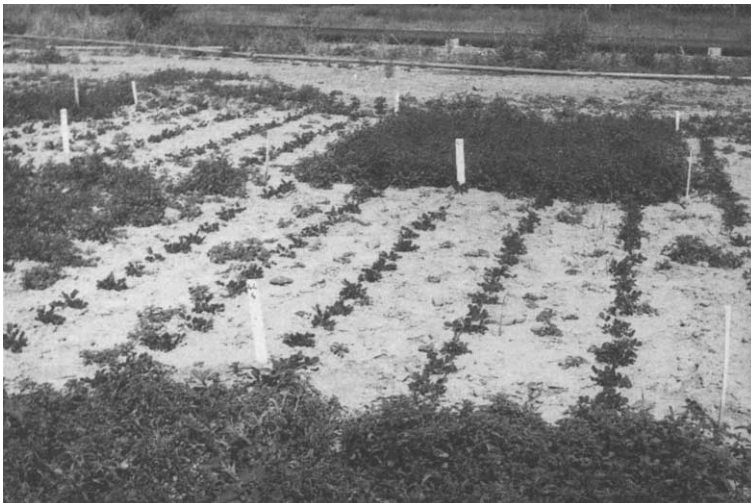


Fig. 17.2. Effect of pre-emergence weed control in groundnuts grown on a loess soil. Note untreated plots in foreground, on left, and in background. Photo A. Amir.

tolerance to the herbicide or else, by the time of emergence of its seedlings, the weed killer should have become decomposed and no longer toxic. The weeds near the soil surface having been killed, the field may remain clean until it is disturbed mechanically. The herbicidal effect may also persist for a long time after emergence (Fig. 17.2).

Post-emergence treatments

Herbicides applied in the standing crop must be truly selective. However, undesirable effects on the crop plants can be avoided by directing the spray so as to reduce to a minimum the amounts of herbicide reaching the crop plants, and by using adapted shields for protecting the rows of crop plants.

Formulations

Sprays have a number of advantages over dusts – in particular their greater efficacy and the reduced danger of drift. In certain countries the aerial application of dusts of the hormonal herbicides is forbidden by law. With low-volume spraying, the main disadvantage of sprays – the need for transporting and spraying a large volume of water – has been eliminated.

Many herbicides are sold in granular form for application to the soil, either within a growing crop or for pre-emergence treatment. The solid forms are particularly advantageous where long residual action in the soil is desired. They are also easier to apply and are frequently more selective than sprays.

Various environmental conditions can influence the degree of activation of the herbicide, its effectiveness, and its persistence. For example, EPTC was less persistent in the liquid form under extreme drought conditions than was the granular formulation. By contrast, the spray formulation of amiben was more effective in the control of weeds under dry conditions than was the granular formulation (Cardenas and Santelmann, 1966).

Factors affecting the performance of herbicides

Climatic conditions

The susceptibility of a species to a herbicide depends to a large degree on environmental factors. Any factor that increases herbicidal retention, penetration and absorption by the weeds, will probably increase effectiveness (Hammerton, 1967).

The temperature prevailing after treatment has a considerable effect on the length of time between application and death of the weeds. In general, warm temperatures promote penetration. In particular, the auxin-like herbicides are extremely slow-acting at temperatures below 20°C; their efficiency is also reduced at temperatures above 30°C (Helgeson, 1957). Information on optimum temperatures of application is extremely important in the hot, dry regions.

Low relative humidities reduce the permeability of the plant tissues to the penetration of the herbicides, and high air humidity has the opposite effect. In tests with the diethanolamine salt of maleic hydrazide, it was found that, at 100% relative humidity, absorption was four times as rapid as at 50% relative humidity (Smith et al., 1959).

The combination of too-high temperatures and low humidity is detrimental to the absorption of herbicides: not only does the cuticle tend to become thicker and less penetrable but spray drops dry more rapidly under these conditions (Foy et al., 1967). Light stimulates the opening of the stomata and increases the production of photosynthates which promote the systemic movement of the herbicide in the phloem (ibid.).

Rain shortly before application increases the hydration and turgor of the tissues, thereby increasing leaf wettability and in consequence herbicidal susceptibility (Hammerton, 1967).

Rain occurring shortly after spraying may wash the chemicals off the plants before they have had time to take effect. The minimum time interval necessary between spraying and rainfall depends on the chemical constitution: esters require no more than half an hour without rain to ensure successful application, whilst amines require about six hours, and the metallic salts about twelve hours. It is generally not recommended to spray plants that are wet with dew or from recent rain or irrigation, as the herbicide may then be excessively diluted. However, when dusts are used, foliage that has been wetted gives better adherence and improves the efficiency of the dust.

The main disadvantage of pre-emergence applications of herbicides is their dependence on the weather following application. Rainfall, beyond a certain amount, may leach the herbicide from the effective superficial soil layer, and may even endanger the seedlings of the crop plant.

Shade, under certain circumstances, may affect the effectiveness of herbicide application. Competition for light, following treatment with herbicides, may be important in preventing the recovery of weeds that have been weakened by herbicides (Hammerton, 1967).

Shading combined with a lowering of temperature may reduce or delay herbicide activity significantly. Herbicides such as glyphosate may take several weeks to be effective on shaded weeds (Jordan and Shaner, 1979).

Wind may cause drift of herbicide from the target crop and damage neighbouring susceptible crops, especially when fields are small.

Granular formulations of CIPC, uniformly distributed on the soil, and applied before dodder (*Cuscuta* spp.) was wrapped around the host plant, were found to provide excellent control of this parasitic weed in the field. Partial shade from the crop at the time of application increased the effectiveness of the CIPC. Control persisted beyond the expected soil life of CIPC, because shade from the crop plants inhibited dodder development and the dry soil surface reduced dodder germination (Dawson, 1966).

Edaphic conditions

Semi-arid soils with a low level of organic matter, and in which the dominant clay mineral is kaolinite, have a low ion exchange capacity (Brady, 1974). As a result, soil-applied herbicides are not very strongly adsorbed to the soil particles, and the herbicide concentration in the soil solution is consequently higher. This increases the availability of the herbicide and decreases its selectivity. The herbicides are also more easily leached out of the root zone (Jordan and Shaner, 1979).

For many herbicides, the most important path of entry is through the roots. When herbicides are applied to the soil there is, however, no direct contact with the active surface of the weeds to be destroyed. The chemicals must reach their target by diffusion and water flow – processes which are extremely dependent on weather and soil properties. This explains the considerable variability in the performance of soil-applied herbicides, and the reason for their higher reliability in irrigation agriculture (Hartley, 1964).

Adsorption of herbicides by soil. The adsorptive capacity of the soil for herbicides depends on the quantity and nature of its colloids. The fraction of the herbicide that is adsorbed by the soil is either permanently or temporarily inactivated. Hence, the efficiency of a treatment tends to be in inverse proportion to the adsorptive capacity of the soil for the herbicide concerned. The rates of application of herbicides have to be adjusted accordingly; higher rates for effective weed control are needed in a heavy clay than in a sandy soil, and still higher rates are required in soils with a high organic-matter content.

In general, as the adsorption of herbicides on the clay particles is an exothermic process, increased temperatures result in reduced adsorption by clay and enhanced effect of the herbicide (Harris and Warren, 1964). For example, the phytotoxicity of pyrazone, applied to early sowings of sugar beets in September, is greater than at later sowings, when temperatures are much lower (Horowitz, 1966).

Losses of herbicides

When the herbicides are surface-applied to dry soils, the very high temperatures of the soil surface under the strong sunshine in the arid regions can cause considerable losses by volatilization and possibly photodecomposition (Hartley, 1964).

Volatilization

The rate of volatilization differs for different herbicides – a factor to be taken into account when choosing the appropriate herbicide. For example, the ester of 2,4-D is approximately 20000 times more volatile than monuron (Klingman, 1961). At a temperature of 60°C, losses by volatilization after twenty-four hours of exposure were 90% for atrazine and propazine, 30% for simazine, and negligible for prometon (Kearny et al., 1964).

It is of interest to note that many of the volatile herbicides are adsorbed more

strongly by a dry soil than by a moist one; when sprayed on a moist soil, they have to be incorporated into the soil immediately after application in order to avoid the loss of a considerable proportion of the chemical (Horowitz, 1966). By contrast, they can be sprayed on a dry surface with negligible loss; atrazine, for example, can retain its effectiveness for several weeks under dry conditions, whilst it is less effective if sprayed on already moistened soil shortly before the weeds germinate. Similar results were obtained with CDED: losses from a wet soil surface at 44°C were found to be much more rapid than from a dry soil (Taylorson, 1966).

This does not, however, apply to all herbicides: under conditions of high temperature and soil moisture, soil persistence of NPA (N-1-naphthylphthalamic acid), amiben (3-amino-2,5-dichlorobenzoic acid), and DCPA or dacthal (dimethyl ester of tetrachloroterephthalic acid), was found to vary inversely with their volatility (Cardenas and Santelman, 1966).

Photodecomposition

Many trials have shown that solar radiation, and in particular ultraviolet rays, can degrade many herbicides and attenuate their biological effects (Jordan et al., 1965). However, these effects are less marked in the field than in the laboratory, probably because the micro-relief of the soil and the adsorption process provide some degree of protection against the radiation effects (Horowitz, 1966).

As long as the herbicide remains on the surface of the soil, it is not only subject to degradation, but it also has little or no phytotoxic effect. For this reason, a herbicide with low solubility, such as simazine, is ineffective in arid regions without irrigation (Hartley, 1964). More soluble herbicides, such as atrazine, can at least be washed into the soil by a light shower. Conversely, in regions of high rainfall, soluble herbicides can be leached downwards to a depth at which they become either dangerous to the crop and therefore less selective, or ineffective when leached beyond the root zone. Disappointing results with herbicides applied to the soil have therefore been frequently reported in dry regions in the absence of rains or, conversely, after excessive rains.

If a herbicide, immediately after application, is made to penetrate the soil for a few millimetres, as is possible by applying a light irrigation with sprinklers, not only are losses considerably reduced, but the chemical is concentrated in the zone in which it will do the most damage to germinating weeds, and the least to the cultivated crop. This irrigation will, incidentally, also cause the weed seeds in the surface layer of the soil to germinate. For these reasons, soil-applied herbicides (in particular for pre-emergence treatments) are most widely used in areas in which intensive irrigation agriculture is practised and where labour costs are high (Hartley, 1964).

Methods of application

Three major problems with herbicide application are spray drift, volatility, and phytotoxic residues in the soil (Burnside, 1979).

Equipment

The major drawback of conventional sprayers is that they rely on constant pressure and forward speed to maintain a constant application rate; it is, however, very difficult to maintain a constant speed. A major advance in sprayer design is adjusting nozzle output to speed changes [automatic volume regulation (AVR)]. The application rate can now be controlled with great precision (and cost!) (Southcombe, 1980).

Mechanical incorporation

Soil-active compounds should be incorporated into the soil, and thereby activated, as rapidly as possible. This is especially important for volatile compounds, such as EPTC and trifluralin.

Mechanical incorporation is indicated for very volatile herbicides and for those with very low solubility. Soil mixing implements (disks, rotary tillers, etc.) are more effective for incorporating herbicides into the soil than stirring implements (chisels, sweeps) or inverting implements (mold-board ploughs) (Unger, 1990).

Incorporation by irrigation (herbigation)

The depth at which herbicides are incorporated into the soil by irrigation (or rain), depends on soil characteristics, the solubility of the chemical, and the quantity of water applied. To be effective, the herbicides should remain at a shallow depth, just sufficient to protect them from loss by volatilization or photodecomposition. Only small quantities of water are necessary for this purpose (generally no more than 30 to 50 mm); greater amounts will only displace the herbicide to a depth at which they are no longer effective. For less soluble herbicides, it is preferable to give several light irrigations at daily intervals rather than one heavy irrigation, which may leach part of the chemical beyond the root zone (Horowitz, 1989).

Sprinkler irrigation has the great advantage that it is possible to apply exactly the amount of water required to incorporate the herbicide at the optimal depth.

For most herbicides, sprinkler irrigation is more effective than mechanical incorporation, probably because of the former's more uniform incorporation and better penetration (Menges, 1963). When the source of activating water is from above, the downward movement of water carries the herbicide by gravity flow, resulting in a better and more controlled distribution of the herbicide in the soil. With furrow

irrigation, the water flow is sideways and upwards, and there is a tendency for the herbicide to accumulate at the surface of the soil (Cardenas and Santelman, 1966).

The increasing importance of pre-emergence selective weed control confers an additional advantage to overhead irrigation, as compared with surface methods of irrigation. It has been shown that the efficiency of pre-emergence application of several weed killers is greatly increased when the application is followed by overhead irrigation as compared with furrow irrigation.

Drip irrigation results in a highly heterogenous water distribution, with very moist soil under the emitters, and completely dry soil at a certain distance from the drip lines.

Application through drip irrigation systems has proven to be very effective in the moist zone, for herbicides that act through the roots. However, the zone of effective diffusion of herbicides with low water solubility, such as triflurin, is smaller than the zone moistened, leaving part of the weeds in this zone unaffected.

Kempen (1989) reviews the advantages and disadvantages of herbigation (also called chemigation), as summarized below:

<i>Advantages</i>	<i>Disadvantages</i>
Ease and timeliness of application	Requires high-level management
Field entry with wet soils	Requires additional equipment
Reduced cost of application (–50%)	Increased environmental hazards
Reduced energy consumption (–90%)	Wind more of a problem
Reduced soil compaction	System leaks may result in loss
Compatible with no-till programmes	of area for several seasons

The major drawback of applying herbicides through any closed irrigation system is the danger of polluting the domestic water supply; the danger is especially acute when a sudden drop in pressure occurs and the treated water can move back into the main pipe system (Horowitz, 1989).

Problems resulting from the use of herbicides

Persistence of herbicides in the soil

The two major problems of concern are (a) whether any of the herbicides are so resistant to degradation by micro-organisms that they become ‘bioaccumulated’; and (b) whether any of the compounds will affect the activities of useful micro-organisms in the soil, and thereby affect soil fertility (Lynch, 1983).

Degradation of herbicides

Herbicides in the soil may be destroyed by micro-organisms, may decompose chemically or by photodecomposition, may be inactivated by adsorption on the soil colloids, or may be lost by leaching or volatilization (Klingman, 1961). The principal factor involved in the degradation of the herbicides is *biological*. Decomposition of herbicides to subtoxic levels by soil micro-organisms may require a few days or up to a year or more.

In general, well-managed irrigated soils are warm, moist, fertile, and well-aerated – conditions that are conducive to the rapid decomposition of organic herbicides. By contrast, in unirrigated agriculture, during the extended periods when the soil is dry, microbiological decomposition may cease completely.

The persistence of herbicides in the soil varies considerably according to their chemical composition. Paraquat and diquat are almost immediately decomposed. Most of the phenoxy group of herbicides are rapidly decomposed in the soil, whilst simazine and diuron are very persistent. Endothal (disodium 3,6-endoxyhexahydrophthalate), applied as a pre-emergence treatment for sugar beets, remains herbicidal for two to three weeks only; it is possible to sow cotton approximately six weeks after a soil application of dalapon plus 2,4-D. By contrast, atrazine applied at the beginning of the rainy season in a winter-rainfall region, may effectively control weeds throughout the winter months, and even throughout the growing period of sorghum that is sown in the following spring (Horowitz, 1966).

Residual effects

The problem of the persistence of herbicides in the soil has two contradictory aspects: persistence is desirable in order to ensure a weed-free environment for as long as possible, but it is undesirable if it interferes with the sowing of a susceptible crop following the crop for which it had been used. In addition, the build-up of residues may reach toxic levels for most, if not all, crops.

The detrimental effects of herbicide residues are usually more serious in arid than in humid regions, and in rain-fed agriculture more than under irrigation. The erratic and unpredictable rainfall of the semi-arid regions makes it difficult to forecast the time that will be required for the breakdown of a herbicide to innocuous levels. The long dry periods may permit persistence of herbicidal activity, which may then interfere with cropping schedules.

In Nebraska, phytotoxic concentrations of simazine and atrazine were found to have accumulated in the subsoil 16 months after treatment (Burnside et al., 1963). 2,3,6-TBA (2,3,6-trichlorobenzoic acid) was found to destroy soybeans five seasons after application. Monuron reduced oat yields in the third growing season after its application (Burnside et al., 1963). Though less dangerous in irrigated agriculture, toxic build-ups may still occur there. In California and Arizona it was found that annual applications of diuron or monuron for eight consecutive years on irrigated cotton had not resulted in a build-up of residues to a level that would be toxic to the

cotton. However, cereals were adversely affected after a single year's application (Arle et al., 1965).

The build-up of herbicide residues to a toxic level can be at least partly overcome by dilution (tillage, irrigation), accelerating breakdown (adding organic manures or maintaining a favourable soil moisture régime), or sowing a non-susceptible crop, and, mainly, by careful use of the herbicides themselves through accurate dosage and calibration, appropriate choice of herbicides. In order to prevent the accumulation of chemical residues in the soil to a dangerous level, and in order to avoid causing shifts in weed populations, it is recommended to rotate different herbicides whenever this is feasible, and to combine chemical weed control with appropriate cultural practices.

Induced resistance to herbicides

In the early 1970's, it was still possible to state that "unlike insects, weeds have, up to the present, only rarely developed strains that are resistant to the chemicals which are used for their eradication" (Arnon, 1972).

According to Day (1966) the main reason for the difference between insects and weeds in developing resistant strains, is probably because the development of resistance is an evolutionary process, requiring a minimum number of generations; this is achieved in a far shorter time by most insects than plants, which normally produce only one generation a year.

However, already in 1965, Longchamp reported that, in fields of maize that had been regularly treated with simazine from 1957, plants of *Panicum crus-galli* had become resistant to doses of 9 kg/ha of active material, whilst originally, complete control of this weed was achieved with only 2 kg/ha. In 1970, Horowitz confirmed (personal communication), that he had isolated several strains of *Cynodon dactylon* which differed in their sensitivity to dalapon, after several years of treatment with that herbicide.

Notwithstanding these warning signals, "weeds that had evolved resistance to herbicides were regarded as interesting phenomena that were appropriate subjects for academic research but of little consequence to the agricultural and horticultural industries" (Putwain and Mortimer, 1989). Gressel (1987) confirms that there was a high level of complacency among research workers, as in almost most cases, suitable alternative herbicides were available to control the resistant weeds.

By the end of the 1980's, 94 weed species were known to have developed resistance to herbicides. This resistance has evolved in spots, both in the humid and in the dry regions (Putwain and Mortimer, 1989).

Concern with the problem has increased: the available alternatives were far more expensive than the original herbicides, sometimes ten times as much (Ammon and Irla, 1984); resistance to some of the replacements has evolved very rapidly (Gressel, 1987); there has been a progressive increase during the 1980's in the number of classes of herbicides to which resistance has evolved, in the number of resistant strains of

different weed species, and in the number of geographic locations in which the process has occurred, and, most worrisome, herbicide cross-resistance has become a problem in some areas (Putwain and Mortimer, 1989).

One example of the serious consequences of resistance to herbicides is the evolution of many resistant strains of *Lolium rigidum* and *Avena fatua* which is threatening wheat production in Australia. Resistant strains of *L. rigidum* show cross-resistance to several other herbicides which differ in their mode of action (Putwain and Mortimer, 1989).

Putwain and Mortimer (1989) suggest the following tactics which can help to delay the appearance of herbicide resistance: (a) the use of herbicides, in rotation, with different sites of action; (b) tillage should be used, wherever possible, to provide differential selection against resistant biotypes; (c) herbicides that induce negative cross-resistance should be included in rotations where resistance to a particular herbicide is expected to evolve, or has already appeared; (d) farmers should have weed populations tested for resistance as soon as weed control becomes less effective.

Long-term strategies to delay and contain resistance are described by Gressel (1987). They involve (a) lowering the selection pressure so as to allow more susceptible individuals to remain alive and thereby dilute the amount of seeds produced by the resistant types (the susceptible individuals are generally more fit than the resistant types and produce more seed); (b) mixtures and synergists allow the use of lower doses of herbicides which are resistance-inducing and thereby lower selection pressure; (c) herbicide rotation makes it possible to suppress herbicide-resistant weeds in the years in which alternative herbicides or tillage are used.

Effect of herbicides on the yield of crop plants

In addition to the indirect effect of the herbicides on the cultivated crop, as a result of the removal of weed competition, a certain amount of herbicide usually reaches the crop plant, and its direct effect on the crop is therefore of importance. These concentrations are naturally sub-lethal even in the case of sensitive crop plants. It has been found in many cases that, at these concentrations, many herbicides have a stimulating effect on growth, and may improve yields independently of the effect of weed removal (Wort, 1965).

Crops that depend on insects for pollination, may have reduced fruit set if populations of pollinating insects are reduced by the control of weeds (Robinson, 1980).

Effects of herbicides on plant composition

Herbicides can affect the composition of crop plants in a number of ways:

- (1) By causing changes in metabolism, resulting in quantitative changes in the amounts of some of the metabolites produced.

- (2) The formation of unusual compounds may occur, following the action of certain herbicides.
- (3) Some herbicides may cause alterations in the physical properties of the cell walls and in the permeability of cell membranes, and, as a result, water and nutrient uptake may be influenced (Brian, 1964).
- (4) Residues of the herbicide itself, or its derivatives, may remain in the agricultural product.

Many herbicides have been found to influence the plants' contents of sugar, starch and protein, usually with the result of improved quality (Wort, 1965). In particular, a favourable effect on the protein content of the grain in wheat, barley and maize, following the application of 2,4-D, has frequently been reported (*ibid.*). Moisture content is generally increased following herbicide application (*ibid.*). On the other hand, oil content is usually decreased, as, for example, in the seeds of linseed (Dunham, 1951).

Changes in crop management following herbicide use

In the past, crop production practices grew around cultivation and crop rotation as means of controlling weeds. The advent of herbicides has given farmers considerable freedom in the choice of production methods and has had an impact on the latter, transcending the role of the herbicides in controlling weeds (Robinson, 1980).

Choice of varieties and crops

A new criterion in the choice of varieties is their relative susceptibility to the herbicides required for the control of the major weeds that infest the crop.

The existence of genetic diversity for tolerance to certain herbicides is widespread in many crops and may lead to the selection of cultivars that are tolerant to specific or to wide-spectrum herbicides (Faulkner, 1976). This may be less expensive than developing new herbicides adapted to a specific crop (Robinson, 1980).

Extremely labour-intensive crops, such as sugar beets, could probably not be grown in modern agriculture without herbicides. Presently, sugar beets can be grown without any hand labour, by a combination of pelleted monogerm seeds, precision drilling and herbicide application.

The dwarf stature and erect leaves of the high-yielding dwarf varieties of wheat and rice contribute to luxuriant weed growth. These varieties, which, in the past, could not have competed effectively with weeds, can now be sown safely.

Crop rotation

Frequently, wide-rowed crops had to be included in the rotation, to make the control of certain weeds possible. The range of herbicides that is now available, has turned

what were formerly considered to be 'fouling crops' into 'cleaning crops'. This has led to increased monoculture of closely planted cereals, such as wheat.

Tillage

As a result of numerous studies on methods of utilizing herbicides in semi-arid areas for weed control during fallow periods, 'chemical fallowing' is in many cases replacing the traditional clean-tilled fallow and even the newer methods of mechanical stubble-mulch farming (Wiese et al., 1967). With chemical control of weeds in fallow, yields were identical to those obtained from conventional tillage (Baker et al., 1956). Chemical fallow greatly increases the crop residues that are available for wind-erosion control. With an initial amount of residue after harvest of approximately $2\frac{1}{2}$ t/ha, after 11 months: chemical fallow left 80% of this, sweep tillage left 66%, and disking left less than 3% (Wiese and Army, 1958).

Chemical fallow reduces tillage operations, not only during the fallow period, but also subsequently in the growing crop. For example, when propazine was applied to wheat stubble, it was found that three tillage operations during the fallow period were eliminated, as was one in the following sorghum crop. Seed moisture at storage and sorghum yields were the same as those obtained by traditional tillage during fallow and inter-row cultivation of the sorghum crop (Wiese et al., 1967).

Seedbeds and sowing

When pre-emergence treatments are anticipated, the seedbed has to be prepared accordingly; direct seeding can replace planting, and sowing to a final stand can replace high rates of sowing with subsequent thinning. In general, rates of sowing and distances between rows can be reduced when the farmer is certain of a relatively weed-free stand. Depth of seeding has to be adjusted to the depth of herbicide placement.

The need for sowing companion crops with legumes, in order to help with their establishment, has frequently become superfluous.

Many vegetables can now be grown on beds, and all cultivation is done before sowing (Robinson, 1980).

Mechanical harvesting

The weed-free crops made possible by herbicide application also enable combine harvesters to work more efficiently and facilitate the preparation of grain for storage or sale (Robinson, 1980).

Effects on plant diseases

Some soil-applied herbicides have been found to increase the leakage rate of meta-

bolites from the roots and thereby provide substrates for pathogens. About two dozen diseases are already known to be increased by herbicides (Lynch, 1983).

Toxicity

Herbicides are generally less toxic than insecticides, but some of them are now suspected of being carcinogens (Tschirley, 1979).

Implications of herbicide use in developing countries

Hoeing and hand weeding are probably the oldest agricultural operations, and the back-breaking work involved still forms a considerable and inevitable part of the human effort involved in subsistence agriculture. Weeds grow very fast in the warm semi-arid regions, and constitute a major handicap in agricultural production. The need to keep the crops relatively weed-free is the dominant factor that limits the amount of land a family can cultivate to tiny holdings. With traditional methods, a man can only cultivate 3 to 5 ha a year (Watters, 1971).

The problem is further aggravated by the commonly accepted dictum that weeding is degrading work for men, so that only women and children are available for this back-breaking chore.

In shifting cultivation, weed infestation generally increases until it becomes unmanageable, and the only practical solution in the past was to abandon the land for long periods, until the regeneration of forest or brush depressed and finally controlled weed growth. With increasing population pressure, this is no longer a viable solution (cf. p. 365) and a suitable weed control method may be the key to enable the transition from shifting to sedentary farming.

Subsistence farmers cannot cope effectively with weeds using traditional methods. The major adverse effects of weeds occur in the first weeks of crop growth, and weeding by hand or hoe is a slow business. By the time the farmer has completed his first weeding, the potential yield of his crops has been depressed by between one-third and one-half.

Not only is the farmer unable to cope effectively with weeds using traditional methods, there is no possibility of adopting yield-increasing inputs, such as fertilizers, because they increase the luxuriant growth of weeds. Nor is it possible to grow high-yielding varieties of wheat, rice or sorghum, which are entirely incapable of holding their own against weeds, because of the low stature and erect leaves of the former.

A solution to the weed problem is therefore of the utmost urgency for the developing countries. The problem of weed control can best be overcome by combining a suitable cropping system, a sequence of cultural operations in coordination with the rainfall season, and judicious use of herbicides (Francis, 1979). However, the domi-

nant system of crop production in the developing countries is based on mixed cropping, preventing the use of crop-specific selective herbicides.

In view of the foregoing, the most promising solution appears to be the use of a general-purpose herbicide, applied before planting, that can provide a weed-free field for three to four weeks after planting.

A pre-planting herbicide has the advantage that its use does not require the same degree of sophistication and does not involve the difficulties encountered in the use of selective post-planting herbicides. The use of the latter could be confined to high-value commercial crops.

The search for such a reasonably priced herbicide and the determination of the most effective and appropriate method of application, should have the highest research priority. In view of the vast array of herbicides, a successful quest should not present great difficulties (Arnon, 1987).

Weeds as useful plants

Chacón and Gliesman (1982) point out that weeds also have beneficial effects. Weeds are ecologically adapted to colonizing harsh environments and improving conditions sufficiently to permit the establishment of less tolerant useful species. Weeds are able to provide soil cover for erosion control. They slow the loss of nutrients, increase organic matter in the soil, provide shelter and food for beneficial organisms, and serve as a genetic pool providing important traits for breeding programmes.

These authors mention that farmers in the lowlands of south-eastern Mexico distinguish between good and bad weed plants (*buen* and *mal monte*) and deliberately do not remove all weeds from many of their cropping systems.

These farmers even use a legume, *Stizolobium deeringianum*, considered elsewhere as a weed, to combat the bad weeds! Planted in rotation with maize, within six months it eliminates the undesirable weeds and improves soil fertility. A fallow period of four to five years would be needed to achieve similar results. It can, of course, be argued that the definition of weed no longer applies to *Stizolobium* used in this way.

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CHAPTER 18

Insects and Other Plant Pests

Insects

Insect species are so numerous, and their adaptations are so varied, that every cultivated crop is attacked by a complex of insect species (E.H. Smith, 1979). The biological success of insects within the animal kingdom is due to their short life cycle, high reproductive capacity, inherent variability and wide adaptation.

Modern agriculture has favoured insect attacks by monoculture, high levels of plant fertilization, the uniformity of high-yielding cultivars, and, possibly most important of all, indiscriminate chemical control measures that have decimated natural enemies which formerly held the insect populations in check.

Adaptations to aridity

The adaptations of insects to aridity include morphological, behavioural, physiological, and ecological modifications (Cloudsley-Thompson, 1975).

Morphological

Adaptations to water loss. There are many striking morphological similarities in the adaptations of plants and insects to arid environments: the creation of a boundary layer by hairs, scales, etc., that reduces absorption of heat from the environment; resistance to loss of water through stomata and spiracles, respectively; surface–volume relationships (Hadley, 1970).

Adaptations for living in sand. Some species have adapted for burrowing, others for running on hot surfaces by appropriate modifications of the body form and of the legs (Edney, 1974).

Colour. The colours of most typical desert insects are either those of the desert itself – ochre, brown, or sandy grey – or else they are predominantly black. The desert colours characterize those insects that are relished by predators, the black insects being generally distasteful.

Though the prevalence of a black colour in desert diurnal insects (and other animals), indicates that this trait must have some positive adaptation value, its significance is still not well understood.

Bodenheimer et al. (1953) examined the transmission of solar radiation through the integuments of several desert species. The results were found to be surprisingly uniform, showing negligible transmission in the ultraviolet range, a slow rise in the visible portion of the spectrum, and high transmission in the infrared range. The authors could not define any benefit arising from the infrared radiation, which supplies heat to the insect. The amount of ultraviolet transmission is so negligible, that any reduction cannot be of significant physiological importance. There is some speculation that the black colouration may reduce transpiration, but this has not been substantiated.

Protection of eggs, larvae, and pupae. Examples of adaptation to the harsh conditions of the desert are eggpods, larval cases, and pupal cocoons, which are constructed of materials that give effective protection.

Behavioural

Behavioural adaptations consist mainly in insects maintaining themselves in favourable microhabitats for most of the time; feeding is confined to those hours, and mating to those seasons when conditions are the least adverse.

Underground existence. Many insects of the arid regions spend much or all their time underground, or under stones, where they can find a more favourable microclimate than in the open.

Aestivation. Phenological mechanisms permit insects to take maximum advantage of short, climatically favourable seasons, and are actually adaptations enabling the insects to avoid stress situations.

Many insects species of the arid regions are capable of remaining in a state of dormancy for extensive periods during periods of dryness, excessive heat, or hot winds. This adaptation is very similar to that of the ephemeral plants. Actually, insects and plants appear together and conclude their lifecycles in the very short period during which favourable conditions occur. This may also occur to insects living on or in cultivated species – for example, *Sesamia* larvae parasitizing dryland sorghum will become dormant in summer within the stalks, whilst on irrigated sorghum dormancy occurs much later (M. Vermesh, personal communication).

Sometimes it is the eggs that remain dormant, even for several seasons, until sufficient rainfall occurs. One example of this is the locust *Schistocerca gregaria*.

Food storage. Many of the insect species of the desert are carnivorous and capable of storing their prey for their progeny, as a supply to be used during adverse periods. The phytophagous insects have adjusted their lifecycles to those of the ephemeral

plants of the desert, or accumulate stores of plant food, or feed on a wide variety of plants.

Physiological

Physiological adaptations that are common to plants and animals of arid environments include “tolerance to high temperatures, facultative hyperthermia, relatively low cuticular and respiratory transpiration, efficient salt excretion, atmospheric water uptake, conservation of metabolic water, and resistance to desiccation” (Cloudsley-Thompson, 1975).

None of the desert insects possess all these traits, but all have a combination of characteristics that enables them to maintain optimum temperature and water balance under adverse conditions (*ibid.*).

Some insects are physiologically so well adapted to arid and semi-arid conditions that humid conditions are actually harmful to them. Examples of this phenomenon are the chinch bug *Blissus leucopterus* and the pale western cutworm (*Porosagrotis orthogonia*). The former is a major pest of the gramineous crops, which under humid conditions is held in check by a fungus (*Sporotrichum globuliferum*). The intensity of infestation of the latter pest depends on the amount of rainfall in the preceding summer: when precipitation is less than a certain amount, a heavy outbreak occurs.

Influence of ecological factors

Lack of stability of desert environments

Ecological theory states that difficult and extreme environments such as deserts, to which only a few species can adapt themselves, are characterized by a lack of stability, whilst complex environments, with many interacting species, have a relatively high degree of built-in stability. A typical example is the extreme fluctuations of locust populations, from a “very low population level to virtual population explosions” (Cole, 1966).

Effects of temperature

The warm season of the semi-arid and arid regions is usually characterized by high temperatures and a low air humidity during the daytime, with a considerable drop in temperature during the night.

High temperatures, if not excessive, accelerate the developmental cycles of insects, and in certain cases the fluctuations in temperature may even increase the effect of high temperature. Hence, there tends to be a larger number of generations per year in these regions than in those with temperate climates. For example, the optimum temperature for aphid reproduction is about 26°C and their lifecycle is shortened and their activity increases as temperatures increase.

Hot weather stimulates the aphids to move frequently during the daytime, as the plants wilt or their palatability decreases. This increases the rapidity of spread of

viruses of which they are the vectors. However, still higher temperatures have adverse effects on the aphids, and at 32°C they cease to infest crop plants and virus spread becomes negligible. Such hot weather also decreases the infectivity of individual vectors (Broadbent, 1967).

Effects of irrigation on insect populations in arid regions

Effects on number of species and on population levels

In an arid environment, irrigation causes profound changes in the nature of the vegetation, both cultivated and spontaneous, as well as modifications of the microclimate, which are bound to affect the nature and number of the insect population. The insects are favoured by the continuous supply of fresh food and the possibility of surviving, between crops, on the weeds of irrigated lands. Intensification of agriculture in arid and semi-arid zones therefore inevitably causes an enormous increase in the numbers of insect species attacking crops – many of them autochthonous or anyway native, whereas others are imported.

The predators and parasites of autochthonous pests are usually also present, whilst imported pests are frequently separated from their natural enemies.

A few years after irrigation was initiated in a desert area of Arizona, 73 insect species were identified as pests of the cultivated crops (McKinney, 1939). And in addition to increasing the number of different species, irrigation is also conducive to enormous increases in insect population numbers.

In arid regions, the rainy season, which is favourable to the breeding of insects, is relatively short. During the dry season, adverse physical and biological conditions cause high mortality; indeed many insect populations are hardly able to maintain themselves under these conditions (Joyce, 1955). Irrigation extends the period that is favourable for breeding, and at the same time reduces or completely eliminates conditions which check the increase in numbers of insect populations. In the absence of natural checks or effective control, epidemics may break out.

In Arizona (USA), wide variations in the degree of infestation by the two-spotted spider-mite, *Tetranychus bimaculatus*, were observed between plots of lucerne receiving different amounts of water. The plants grown under the most favourable moisture régime had the most mites, and infestations were far lower in the relatively 'dry' plots.

The influence of the different irrigation schedules upon mite population is believed to be both ecological and nutritional. The sparse growth of the lucerne grown under relatively dry conditions allowed the sunlight to penetrate to the ground surface, and as a result air temperatures 15 cm above the ground were markedly higher and relative humidities were very much lower in the dry plots than in those more frequently irrigated. The hardened, sparse growth of the lucerne grown under conditions of moisture stress was apparently nutritionally less favourable for the mites than the lush growth of the well-watered lucerne (Butler, 1955).

Irrigation in Israel, together with the concomitant introduction of new cultivars, and reduction in acreage of rainfed crops, has brought about drastic changes in the insect pest complex (Rivnay, 1963). For example, a survey by Melamed-Madjar and Tam (1980) showed that the population size of *Chilo agamemnon*, previously the main pest of maize, had decreased, as well as that of *Sesamia cretica*, an important pest of dryland sorghum. Conversely, *Sesamia nonagrioides*, has proliferated, and became the major pest of all maize cultivars.

The continuous supply of fresh food, made possible by irrigation, at a time when temperatures are favourable for the rapid evolution of insects, engenders an increase in the number of generations in a year. For example, the beet weevil (*Lyxus junci*) became a major pest with the extension of irrigated stock beets, producing three generations a year instead of the single generation in spring that was the case before irrigation was introduced (Rivnay, 1963).

The transition from relatively harmless insects into major crop pests was not a gradual process, but occurred explosively as soon as a continuous supply of fresh food became available (M. Vermesh, personal communication, 1968).

On the other hand, crops are sometimes less damaged by insect attacks when irrigated than when grown under a drier régime. For example, ranger lucerne was more tolerant to leafhoppers when an adequate water supply was available than when it was grown under conditions of water stress (Wilson et al., 1955). Sprinkler irrigation may reduce a thrips population by about 50% (R.F. Smith, 1957).

Arid regions as barriers to the spread of insect pests

Arid regions can form a very effective barrier to the spread of certain insects. For example, the pink bollworm (*Platyedra gossypiella*) has been established in Egypt for almost half a century, but it did not cross the Sahara and infest the cotton fields of West Africa. That this was not due to adverse ecological conditions in the West African countries is indicated by the fact that, after the pink bollworm was introduced with infested seed samples sent by post, it spread rapidly in the countries to the south and west of the Sahara (Vayssière, 1954).

Canals that cross desert regions serve as routes for the infestation of irrigated areas within the desert by insects which, because of the lack of adaptation to dry conditions, could not have reached such areas otherwise. An example is the cucumber beetle (*Diabrotica balteata*), which has spread widely in irrigated areas of California, along the irrigation canals (McFarlane et al., 1957).

The development of irrigated 'oases' in the desert creates bridges which facilitate the migration of pests across the desert. The beet leafhopper (*Circulifer tenellus*), the carrier of the curly-top virus disease, migrates long distances over desert areas by this means (Carter, 1961).

Drylands as reservoirs of potential insect pests

The drylands can also serve as reservoirs, from which insect infestations may develop

and then come to damage adjacent irrigated areas. Following the introduction of irrigation in the geographically isolated Salt River Valley of Arizona, certain insect species that originally subsisted on wild native host plants increased in abundance and became adapted to the cultivated crops, whilst many other species were introduced by natural dispersion or by artificial carriage (McKinney, 1939). Many insects migrate over long distances, from their normal habitats in arid lands, to neighbouring irrigated or semi-arid rainfed cultivated fields.

During the dry season, many moths migrate at night in mass flights from arid habitats in which they breed during the favourable parts of the year, to irrigated or higher-rainfall areas (Uvarov, 1962). Examples of this phenomenon are the cotton leafworm (*Alabama argillacea*) and *Agrotis ypsilon*. The adults of the former come annually, probably from arid parts of Central America, to the southern United States, where they produce several generations which cause considerable damage to the cotton crop, before finally disappearing (Fenjves, 1950). The latter insect, a serious pest in Israel, immigrates annually from unknown sources, multiplies in cultivated crops, and then disappears (Bernard, 1954).

In the southwestern United States, the beet leafhopper overwinters in desert areas that usually receive winter rainfall. In late spring this population migrates to newly sown irrigated sugar beet fields, infecting the crop with beet curly-top virus (Siegel and Hari, 1980).

A typical case of an insect for which certain desert regions are the natural habitat, but which may become a major pest of cultivated areas far beyond the fringe of the desert, is the desert locust (*Schistocerca gregaria*) (Fig. 18.1). This locust requires moist sand in which to lay its eggs, sufficient green, tender food for the young hoppers, and succulent green food or high air humidity for reproduction (Bodenheimer et al., 1930). These requirements are certainly not typical for desert conditions, but they are met in ephemeral ecological islands. Therefore, the survival of the desert locust is dependent on the ability of the insect to move from one favourable habitat to another – a nomadic habit very similar to that of many desert mammals.

A grown locust is capable of eating daily its own weight in food. Large swarms may weigh up to 50 000 t, and may have eaten about ten times their own weight of vegetation while growing (Cloudsley-Thompson, 1969). The migratory locust was a major pest in most of Africa south of latitude 20°N, until the 1940's. The discovery that the outbreaks originated in a relatively small area in the floodplains of the Niger river has made possible continuous monitoring of the area, and consequently the destruction of the swarms before they can escape (Wickens and White, 1979).

Land development schemes in the desert, based on irrigation, may easily change precarious and ephemeral ecological islands into more or less permanently favourable breeding grounds for the locusts (Uvarov, 1954), thereby enabling the pest to become still more dangerous than in the past. The Rocky Mountain grasshopper (*Melanoplus mexicanus*) normally produces a single generation annually in the deserts of Arizona. The extensive cultivation of lucerne under irrigation has, however,



Fig. 18.1. Locust swarm. Courtesy Soil Conservation Service, Israel.

made it possible for the grasshopper to produce several generations a year, and it can now only be kept in check by an expensive chemical control programme (ibid.). The effect of land development in the desert on the increased incidence of this locust is probably not an isolated example, but an indication that irrigation schemes in the desert may well create new, unanticipated entomological problems (ibid.).

Many other insects, feeding on the native vegetation of arid and semi-arid regions, have become important pests of cultivated crops. A few examples are the wheat thrips (*Haplothrips tritici*), which is abundant in wild perennial grasses in Kazakhstan (Uvarov, 1962), the sorghum midge (*Contarinia sorghicola*), a pest that causes severe damage to sorghum in arid regions and is closely related to a genus that occurs on wild sorghum and allied species (Barnes, 1954), the cotton boll weevil (*Anthonomus grandis*), which has spread into the cotton growing regions of the United States from desert regions of Mexico in which its host plants are wild cotton species (Uvarov, 1962), and the beet leafhopper (*Circulifer tenellus*), which is the vector of curly-top virus in sugar beets, having migrated to the fields of the cultivated crop in the southern United States from the desert where it feeds on sagebrush (*Artemisia*) and salt-bushes (Lawson et al., 1951).

Preferential feeding on irrigated crops

In general, insects pests are more attracted to the succulent growth of irrigated crops than to the hardened, sparse growth that is characteristic of plants grown under conditions of moisture stress.

For example, irrigated cotton was more heavily infested by three species of mirids – the cotton fleahopper (*Psallus seriatus*), the rapid plant bug (*Adelphocoris rapidus*), and the tarnished plant bug (*Lygus lineolaris*) – than was unirrigated cotton (Adkisson, 1957). Infestation by the stem-borer of wheat (and rice), *Sesamia inferens*, in India, was far greater on irrigated than on unirrigated wheat (Chowdhury and Sharma, 1960). Irrigated wheat was found to be more attractive than non-irrigated wheat to the hessian fly (*Mayetiola destructor*) and to the frit fly *Oscinella frit* (Pavlov, 1959).

Fertilizers in relation to insect control

Insects are not affected in the same way as pathogens, or as higher animals, by mineral deficiencies in the plants on which they feed. In contrast to fungal and bacterial pathogens, insects have digestive and excretory systems and their dietary requirements are less specific (Marschner, 1986).

Mineral nutrition can affect all aspects of plant resistance to insects in various degrees. The intensity of attack by sucking insects will depend on whether fertilizers increase or decrease the content of soluble organic N in plants (Marschner, 1986).

Huffaker et al. (1969) have shown that the effect of N on red spider mites is not consistent because it is dependent on additional factors. For example, increased N is associated with increased fecundity, decreased fecundity, or has no effect on fecundity, depending on the presence or absence of elements other than N in the soil, and of sugars or related materials in the leaves.

Haseman (1946) claimed that, as insects generally require smaller amounts of minerals relative to their weight, it is quite possible that plants with a low mineral content may be more favourable hosts than those with a higher mineral content. He found that, in a number of cases, a shortage of certain minerals actually proved beneficial rather than detrimental to insects. It was found that chinch bugs mature faster, live longer and are more prolific, when feeding on maize grown under conditions of N deficiency than on normal maize. Thrips have also shown differential preference for plants with a low level of nitrogen nutrition. Wheat-stem sawfly damage was increased by potassium deficiency. Depletion of soil nutrients, associated with irrigation, either directly through leaching or indirectly through increased yields, may therefore increase susceptibility to insect damage, unless offset by appropriate fertilization. On the other hand, heavy fertilization, by increasing vegetative growth, may favour the increase of certain insects, as is the case with the bollworm.

Nitrogen also affects the succulence and tenderness of the tissues of rapidly growing plants. Nitrogen applications at a rate of 88 kg/ha have been shown to produce maize stalks with thinner rinds and consequently higher rates of infection by European corn borers (*Ostrinia nubilalis*) (Zuber and Dicke, 1964).

Silicon: Epidermal cells containing silicon deposits, or soluble silicic acid act as a

mechanical/chemical barrier to the stylet and mandibles of sucking and biting insects (Marschner, 1986).

Methods of insect control

Prevention is better than cure

Pests have frequently been introduced into countries in which they were previously unknown; in spite of the enormous losses caused by the intruders, such cases are still far from uncommon. The increasing dependence of many LDCs on food imports, on the one hand, and lax plant quarantine control, on the other, are exposing these countries more and more to the introduction of new pests. Two recent examples of such introductions are reported by the FAO (1983): the larger grain borer (*Prostephanus truncatus*), formerly found only in Central America and the Southern USA, was discovered in Tanzania in 1981. Losses of maize in storage of up to 30% have been recorded in the newly infested areas. The new pest spread fast and also attacked groundnuts and dried cassava. The eastern mealy bug (*Phenacoccus manihoti*), introduced from South America in 1973, established itself within a decade throughout the main cassava growing areas of Africa, and poses a serious threat to a major component of the food supply of an estimated 200 million Africans.

Cultural practices

Until the advent of insecticides, cultural methods were practically the only ones available to farmers for active insect control. In many countries with primitive agriculture, and an abundance of labour, the collecting and destroying of caterpillars and eggs is still practised on a large scale with cash crops, for example for the control of the Egyptian cotton worm (*Spodoptera littoralis*).

The major cultural practices that have an impact on insect proliferation include time of sowing, sanitation, crop rotation, tillage, sowing trap crops, strip cropping, etc.

Even at present, appropriate cultural methods should not be neglected, and their contribution to keeping the harmful insects at a low level of incidence can be considerable.

In Israel, early spring sowing of sorghum is the principal and most effective method of avoiding disastrous damage by the sorghum shoot-fly (*Atherigona varia*). Conversely, a delay until June in the sowing of maize is an essential precaution for the prevention of 'dwarfness', a virus disease propagated by an insect vector.

Sowing dates can be chosen so as to shorten the growing season, thereby minimizing the exposure of vulnerable crops by reducing the periods during which the pest can multiply. To be effective, local planting dates need to be harmonized and are sometimes coupled with early harvesting and trap crops (Hussey, 1990).

The destruction of weeds, which serve as alternative hosts to certain insects, considerably reduces the sources of infestation of the cultivated crop.

Preparing a good seedbed and providing favourable conditions for rapid and even germination, is an effective method for reducing the damage caused to the young seedlings by soil-inhabiting insects.

Chopping and ploughing-under the stalks and residues of the cotton crop, has been found to destroy 85% of the larvae of the pink bollworm (Fife et al., 1963).

Ploughing to a depth of 15–20 cm is completely effective in controlling the cereal leaf miner (*Syringopais temperatella*), one of the most damaging pests of wheat in the Near East.

Strip cropping sorghum in cotton results in a significant reduction of damage by *Heliothis* spp., because predators of the insect can build up in the sorghum whilst they are destroyed by chemical treatments in the cotton (Massey and Young, 1975).

Planting a resistant variety around a susceptible one may prevent a migrating pest from reaching the latter. Conversely, planting a susceptible variety around a non-preferred one, may serve as a trap crop for the pest. When 10–20% of a field was planted with green-leaved cotton around a red-leaved cotton, which is not preferred by boll weevils, the insects concentrated in the green rows. These were sprayed, whilst the predators and parasites remained effective in the red cotton (Maxwell, 1977).

In general, trap crops occupy only a small proportion of the area of the crop to be protected. For example, to protect soybeans, only 5% of the crop area needs to be planted with snap beans (Hussey, 1990).

Preventive control

The classical example of preventive control is that of locusts, of which two species – the red locust (*Nomadacris septemfasciata*) and the migratory locust (*Locusta migratoria*) – used to cause periodical devastations in Africa and Asia. The foci of infestation of these pests are in relatively restricted areas. By maintaining a constant watch over these potential outbreak areas, it has been possible to reduce the dangers of large-scale invasions considerably (Uvarov, 1962).

The preventive control of the desert locust (*Schistocerca gregaria*) is more difficult, because this locust is nomadic and has no permanently located outbreak areas (Uvarov, 1962). Preventive control, in this case, is based on international supervision of the seasonal movements of swarms in the areas most frequently infested, so that effective control operations can be planned at an early stage.

Insurance control

An important function of insect control is to insure against disastrous losses due to insect pests (Perkins, 1982). The considerable amount of capital invested in farming operations, generally obtained on credit, makes it imperative to reduce the risks carried by the farmer and his creditors. Reliable insect control is expected to provide the required insurance.

However, pesticide treatments by the calendar, without knowing whether they are necessary, can do considerable ecological harm. By contrast, prophylactic seed treat-

ments with insecticides or fungicides are ecologically impeccable in providing insurance. The extremely small quantities used per ha cannot significantly affect the natural enemies (Klassen, 1979).

Insecticides

Organochlorides and organophosphates

The insecticides in use in the late 1920's were derived mainly from plants, and included nicotine, pyrethrum, hellebore, quassia, and derris. A few inorganic compounds were also used: arsenicals – extremely effective stomach poisons with high mammalian toxicity – and the less dangerous fluorides.

During the Second World War and the following years, a number of completely new and extremely effective insecticides were developed. The first of these new contact poisons, which penetrate into the insect through the cuticle or trachea, entering the nervous system or the blood systems, was DDT. Though it had been synthesized as early as 1874, its efficacy as an insecticide was discovered only in 1939. It was then noted that it was not only extremely effective in killing a wide range of insects, but that its residual effect lasted for up to one month under field conditions. In the period following these discoveries concerning DDT, a large number of additional compounds were produced and introduced into agricultural practice.

Insecticides can be divided into very *stable compounds*, mainly the organochlorides (DDT, aldrin, dieldrin, isodrin, endrin, chlordane, telodrin, heptachlor, strobane, toxaphene, mirex, etc.), and *non-persistent* insecticides, mainly organophosphates (parathion, systox, TEPP, malathion, chlortion, dibrom, ronnel, dipterex) and carbamate compounds, which rapidly break down into non-toxic products.

The effect of the stable compounds may extend for great distances beyond the sites of their use, and may persist for many years, accumulating in enormous amounts in the biosphere. It has been calculated that 1 500 000 t of DDT are circulating in the biosphere (Dorst, 1972). Because of their low solubility in water and high solubility in lipids, the organochloride compounds are not 'lost' by dilution in water, soil, or air, but, on the contrary, become increasingly concentrated in the tissues of living organism with each step in the food chain. This biological concentration causes levels of organochlorides in organisms that can be millions of times higher than those found in the surrounding inorganic environment (Wurster, 1972). Because of their broad spectrum of biological activity their danger to the environment is considerable.

Certain major effects of contamination by organochlorine compounds, such as extensive mortality among birds, toxicity to fish, reduced photosynthetic activity in certain species of phytoplankton, have been conclusively demonstrated. In insects, their main effect has been to induce resistance in harmful insects and destruction of the numerous predators and parasites of the former. Paradoxically, whilst the immediate effects on harmful insects are dramatically successful, in the long run they destroy the biological balance between phytophagous insects and their natural ene-

mies, so that ultimately they are actually beneficial to the harmful insects (Wurster, 1972).

Other effects, such as inducing cancer and mutagenesis in humans, have not been conclusively proven, but because of the hazards involved, the use of DDT and other organochlorine compounds has been banned in many developed countries. They are mainly replaced by organophosphorous and carbamate compounds.

Whilst these have the advantage of being quickly degraded and do not accumulate in the food chain, some of them are extremely toxic to humans, and all have the same limitations as the stable insecticides in that they disrupt the biological balance between phytophagous insects and their natural enemies, to the ultimate benefit of the former.

The implications are obvious: whilst it is impossible to ban the use of insecticides, more attention must be given to avoiding, or at least mitigating, their destructive effect on the environment. The first step is to replace the stable insecticides by the non-persistent types, and to reduce their use to the bare minimum by combining chemical control with cultural and biological control methods in a system of integrated control.

Synthetic pyrethroids

Until the 1970's most insecticides were nerve poisons. Recent trends are to develop insecticides that disrupt vital physiological processes which are specific to insects and are safe for vertebrates (Tschirley, 1979).

The synthetic pyrethroids are based on the natural pyrethrum of plant origin. First synthesized in the early 1970's, they are characterized by a high activity against insects, low mammalian toxicity, and greatly increased stability (Elliott et al., 1978).

Various pesticides of this group, such as permethrin, fenvalerate, cypermethrin, decamethrin, and fenpropathrin, have a long-lasting effect on pests, but also affect natural enemies; as a result, their use often results in an increase of red spider mite populations (ibid.).

Systemic insecticides

Systemic insecticides can be applied in a number of ways (Ridgway, 1967):

To the seed and in the furrow. These are the most prevalent methods. The insecticides can be applied directly to the seed, and treated seed is already available commercially. A more recent development is in-furrow applications of such systemic insecticides as disulfoton and phorate in granular formulations applied with the seed. In-furrow applications appear to be less phytotoxic than seed treatments, at equal rates per hectare.

Foliar applications. When applied to the leaves, systemic insecticides penetrate the leaves; but as translocation is limited, the systemic action is localized.

Side-dress applications. The uptake of systemic insecticides from the soil depends on a number of factors, including moisture conditions, and is therefore not always very effective. Some compounds, such as temik, can sometimes be very efficient.

Stem applications. Stem applications of systemic insecticides are much more effective than side-dress applications; for example, 22 g/ha of CL-47031 applied to the stems of cotton, gave as good a control of the cotton fleahopper (*Psallus seriatus*) and spider mites as 230 g/ha applied to the soil. A tractor-mounted rotary-brush applicator for treating the stems of plants has been developed.

Antifeedants

Antifeedants are chemicals that inhibit feeding: insects that remain on the treated foliage eventually starve to death without eating the leaves. An example of an antifeedant is brestan (triphenyl tin acetate) which, when used as a fungicide, inhibits the feeding of insects on the treated foliage (Ascher and Rones, 1964). Antifeedants have been reported to be effective against the cotton leafworm (*Spodoptera littoralis*) (Ascher and Nissim, 1964).

The main advantage of antifeedants is that they do not harm the parasites and predators of insect pests. Their main limitation is that they are effective only against surface-chewing insects (D.J. Wright, 1967).

The reproduction–diapause (r–d) control method

Insect control by r–d is a very effective method of applying ordinary insecticides (Perkins, 1982). Instead of applying the insecticide during the growing season, at the time an insect is actively damaging the crop, the insecticide application, in the case of the cotton boll weevil, for example, is timed so as to kill the weevils that might give rise to the generation that will eventually winter and infest the next year's crop. This means, in practice, that applications begin relatively late in the growing season, at a time that the farmer has normally ceased to use insecticides, because the crop is no longer susceptible to boll weevil damage.

The biological basis for control by r–d is the fact that only weevils that achieve a state of diapause (i.e. a physiological state characterized by high fat storage and low physical activity) are capable of surviving the winter. By controlling the generation of boll weevils that produce the individuals going into diapause, a diapausing population is prevented, and infestations in the following season are significantly reduced (Brazzel, 1962).

In a large-scale test of r–d control on the Texas High Plains, a 98% reduction in wintering boll weevils was achieved (Adkisson et al., 1966).

Limitations of insecticides

Resistant strains. For a few years, great successes were achieved with the new insecticides; but gradually their shortcomings revealed themselves. Optimistic forecasts,

predicting the complete extermination of major pests, proved to be premature. Certain insects were effectively controlled, to be replaced by others which had previously been minor pests. For example, the chemical control of jassids (*Empoasca* spp.) on cotton in the Sudan, resulted in an increase of the whitefly (*Bemisia gossypiperda*); when the whitefly was controlled by an insecticide, damage due to cotton bollworm (*Heliothis armigera*) increased markedly (Joyce, 1955). It was shown that three consecutive sprayings with one of the chlorinated hydrocarbons were sufficient to annihilate all the natural enemies of these pests.

Strains resistant to the new insecticides developed within a relatively short period, by an evolutionary process, in more than 200 insect species (Ordish, 1967).

Unfortunately, the most widely used insecticides belong to a few chemical groupings, so that development of resistance to one compound causes redundancy of most of the others of the same grouping (Tschirley, 1979).

Dangers to public health. Meanwhile public awareness of the danger to human health of the residues of certain insecticides, especially after their concentration through 'food chains', has increased. Preventive chemical control (before the appearance of the pest) and routine control (treating 'by the calendar') proved to be not only expensive but also frequently ineffective and even dangerous.

Resurgence. A phenomenon known as 'resurgence' also became increasingly frequent (Chant, 1966). When insect populations increase steeply, stresses due to severe competition cause a marked reduction in reproduction. The obverse is also true: when the population density of a pest is reduced to a low level by an effective chemical control programme, reproduction rates may increase to such an intensity that a population explosion of epidemic proportions occurs. This process is facilitated if the chemicals used have also decimated the natural enemies. It is only when population density is reduced below a certain, extremely low level, that the decline may continue until complete extinction occurs; but it is very unusual to achieve this by the use of pesticides alone.

Biological control

Biological control is defined as "the direct and indirect use of living organisms to control pests and to reduce damage below economic levels" (Chant, 1966). The living organisms employed are insects or pathogens.

A large percentage of insect species prey on other insects, and there is no doubt that the main factor preventing a 'population explosion' of an insect species is its natural enemies. These fall into two main groups: the *predators*, which are usually larger and stronger than their victims, and the *parasites*, which live on or in the bodies of insects that are much larger and stronger than themselves (Fig. 18.2).

The individual predator attacks and destroys numerous individuals of the species

on which it preys. Predators are usually active and agile, but reproduce more slowly than their prey. Therefore, the prey are usually capable of outbreeding their predators (Cole, 1966). By contrast, the parasite is not very active, has a short lifecycle, and usually preys on a single individual victim.

Not all natural enemies of insects are beneficial to Man. The natural enemies of harmful insects have their own predators and parasites which are therefore, ipso facto, harmful from Man's point of view. These, in turn, also have their natural enemies, which are therefore beneficial. The food chains of most agroecosystems form a complex maze often called 'food webs'.

The relationships between insects, their natural enemies, and the hyperparasites, are extremely complicated, and it is easy to understand how Man's intervention can



Fig. 18.2. Example of biological control: a wasp, *Baphyplectes curculionis*, attacking a larva of lucerne weevil. By courtesy of the US Department of Agriculture, Washington, DC.

readily upset the very delicate system of checks and balances occurring in Nature between these components of a biological system (Fig. 18.3).

The biological balance between natural enemies and their hosts is maintained by a density-dependent mechanism, i.e., when the prey population is high, natural enemies have a higher rate of parasitization or predation on their hosts than when the prey population is low (H.S. Smith, 1935). Belief in density-dependent regulation, according to which insect populations oscillated around an equilibrium, was the foundation for confidence in the ability of biological control to function reliably in crop production systems.

It is well known that the natural enemies of an insect species are not capable of controlling it completely (this could lead to their own extinction) or even continuously. Normally, they are able to maintain the numbers of the harmful insect within certain limits, so that it does not cause appreciable economic damage (Biliotti et al., 1962). Under circumstances which favour a very rapid increase of the harmful insect, however, its natural enemies are no longer able to cope with the population explosion, and the intervention of Man, using appropriate control techniques, becomes necessary.

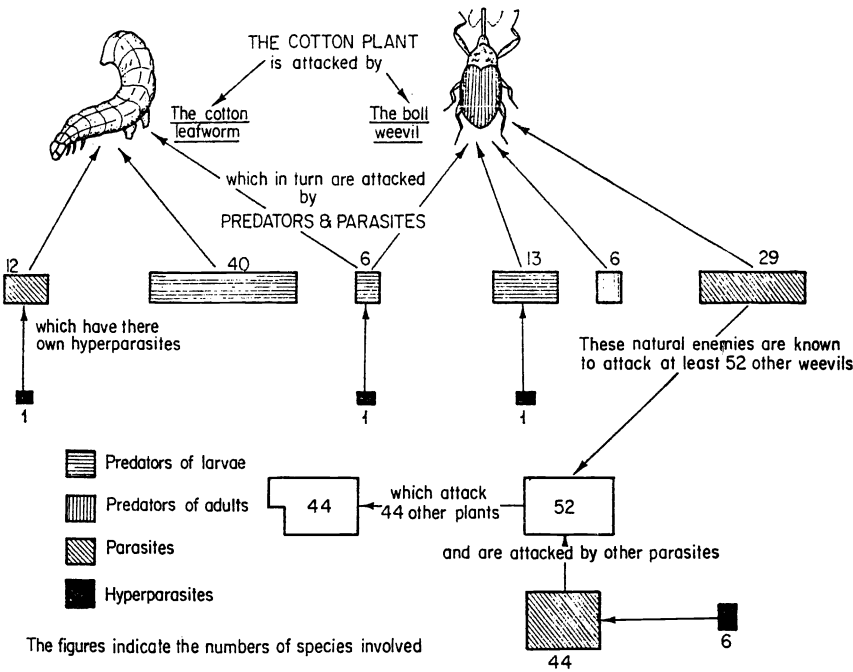


Fig. 18.3. Schema showing some of the interrelationships of helpful and harmful parasites associated with the cotton boll weevil and cotton leafworm. After Pierce (1912). By courtesy US Department of Agriculture, Washington, DC.

There are three basic approaches in the use of parasites and predators, for biological control: (a) introduction; (b) conservation or manipulation of the environment; and (c) augmentation of natural enemies.

Introduction: based on the search for new natural enemies in other regions and usually countries, these are reared and subsequently released. This method has proved its effectiveness especially in the control of harmful insects that had been introduced from foreign countries. As a result of their disassociation from the natural enemies of their native habitat, these may become pests.

The environment can be influenced either by minimizing the effects of factors that reduce populations of natural enemies, or adding lacking requisites so as to improve their natural propagation.

Augmentive biological control consists in artificially rearing natural enemies, periodical releases, genetic improvement of predators and parasites and/or manipulating their behaviour chemically, e.g., by the use of kairomones.

The earliest successful control through the introduction of natural enemies in the USA was in 1888, when a ladybird, *Rodolia cardinalis* and a fly, *Cryptochetum iceryae*, were imported from Australia to control cottony-cushion scale (*Icerya purchasi*) on citrus. Within a year, the scale was eliminated as an economic pest. Since then, the method has been applied many times, in many countries, to control many pests. There have also been failures, e.g. the search for a natural enemy for the cotton boll weevil has not yet given significant results (Sailor, 1979).

Para-biological control

The term 'biological control' is reserved, by convention, to the use of, or reliance on, the natural predators and parasites of insects. However, there are a number of non-chemical methods of control that are biological in nature, such as microbial insecticides, the introduction of sterile males, sex attractants, the use of hormones, and breeding resistant varieties.

Microbial insecticides

Microbial insecticides are suspensions of micro-organisms and/or their products that are specific to certain insects and cause their death. The study of this type of control has expanded considerably, because of the problems of insect resistance, the emergence of secondary pests, and toxic residues that are becoming increasingly acute following the use of conventional insecticides (Tanada, 1967).

The number of successes in this field is still small, and is limited to pathogens with resistant stages that retain their viability for a long time and can be applied with conventional dusters or sprayers. The two most important successes in field crops are the use of *Bacillus thuringiensis* for the control of the European corn-borer (*Ostrinia nubilalis*) and other lepidopterous insects, and of nuclear-polyhedrosis viruses against the lucerne caterpillar (*Colias philodice eurytheme*).

In the avocado orchards in Israel, *Bacillus thuringiensis* is widely used against the giant looper (*Boarmia selenaria*) and the honeydew moth (*Cryptoblabes quidiella*) (Swirski et al., 1988).

Fungi and nematodes are currently being used to control pests, especially soil inhabitants.

Ridgway et al. (1979) report that two viruses are currently approved for farm use in the USA: the *Heliothis* nuclear polyhedrosis virus (NPV), and the tussock moth NPV. Viruses are specific and do not affect the natural enemies of the insect to be controlled, but they have a short field life.

Genetic modifications

Genetic modification of insects can cause sterilization, induce inability to diapause, induce asynchrony in emergence, reduce productivity, change sex ratios, or induce inability to fly. These effects can be achieved chemically or by irradiation (Ridgway et al., 1979).

The sterile-male technique

The eradication of an insect pest was accomplished successfully for the first time by the introduction of sterile males into the natural population when the screwworm (*Cochliomyia hominivorax*) was eradicated on the island of Curaçao in 1955. The method was subsequently applied, equally successfully, in Florida and over vast grazing lands in Texas (Metcalf and Metcalf, 1982).

The method involves the rearing, sterilization, and release of insects in numbers sufficiently large to overwhelm the natural population (Moseman, 1966). The sterilization is achieved by irradiation, chemosterilants, or hybridization.

The two preconditions for the successful application of the technique are: (a) that the insect is relatively rare in nature, and (b) that it is possible to raise large numbers of the insect in the laboratory (Metcalf and Metcalf, 1982).

In contrast to the sterile-male technique, which is only efficient when the target population is small, insecticides can achieve a highly efficient kill rate when applied to large insect populations. Increasing inputs of insecticides follow the law of diminishing returns, whereby each increment of insecticide kills a smaller percentage of the target population. As a result, insecticides cannot eradicate a pest. Knipling (1979) argued that the two techniques could be complimentary: the insecticides could diminish the pest to the low level at which the sterile-male technique was efficient and capable of eradicating the remaining pest population.

Attractants

Insects respond to many chemical, biological, and physical stimuli, which can serve to attract insects and facilitate their control.

Sex attractants. The most potent of these attractants are the sex pheromones of the

insects. Pheromones provide a means of luring insects to their deaths, and some of these attractants may be produced synthetically.

The discovery, isolation, and chemical identification of the sex attractant of the silkworm (*Bombyx mori*), in 1959, was a major advance in insect control; by the end of the 1980's pheromones and parapheromones (pheromone mimics) for over 1000 insects had been identified. The use of pheromones in traps for the detection of specific insects is an accepted tool in many pest management programmes. Lures for over 250 insects are currently available (Ridgway and Inscoe, 1990).

Disruption of pheromonal communication between the sexes with synthetic pheromones has been demonstrated with a number of Lepidoptera, including the Egyptian cotton leafworm (*Spodoptera littoralis*), an important pest of cotton, vegetables, and fruit trees (Kehat et al., 1985).

The citrus flower moth (*Prays citri*) can be effectively controlled by male trapping with the synthetic sex pheromone (Sternlicht et al., 1990).

The use of caged virgin females in black light traps has proved to be very effective with certain insect species.

Parasite attractants. Other potentially useful compounds are kairomones, present in host insects, which provoke the attack by a parasite and thus stimulate the host-seeking activity of the parasite (Plimmer, 1979).

Feeding attractants. Compounds such as methyl eugenol and protein hydrolyzate are used to attract insects, such as the Mediterranean fruit fly (*Ceratitidis capitata*) and the oriental fruit fly (*Dacus dorsalis*), to feed on poisoned baits (Ridgway et al., 1979).

Hormones

Hormones controlling insect development, such as ecdysone and juvenile hormone have been known for many years, but the high expectations for third generation control methods have not yet provided significant alternative control technologies (NAS, 1975).

Hormonal insecticides aim at interfering with essential physiological processes, without necessarily causing death of the insects. For example, treatment with juvenile hormones may interrupt insect development and prevent reproduction, or moulting hormones may cause sterility in adult insects. The quantities required for effective control are extremely small, and are not harmful to other organisms.

Certain ethers, which are juvenile-hormone-like compounds, and fairly easy to synthesize, have been found to be even more potent than the natural hormone (Henneberry, 1979).

Various insect growth regulators (IGRs) of agricultural importance such as buprofezin, cyromazine, fenoxycarb, pyriproxyfen, and benzoylphenyl, have been developed (Ishaaya, 1990).

The search for other materials that interfere with essential processes continues. A

recently introduced chemical inhibits the formation of chitin, leaving the insect without protective covering. At lower doses, the same chemical causes male sterility (Plimmer, 1979).

Chemosterilants

These are chemicals that are administered orally or by contact and produce irreversible sterility in insects, without marked adverse effects on their mating behaviour or viability. This method can be combined with chemosterilant baits, so that sterile males in large numbers are released into the population (Nelson and Seubert, 1966).

Breeding for insect resistance

Plant resistance to insects

The main types of resistance of host plants to insect pests are (Marschner, 1986):

- (a) physical (colour, surface properties, hairiness);
- (b) mechanical: young and tender tissues of rapidly growing plants are more prone to insect attack than older, tougher tissues;
- (c) chemical/biochemical (nutrients, stimulants, repellents, toxins): sugar can act as a feeding stimulant, but amino acids and amides are more important in this respect.

Mechanisms of resistance

Plants through evolution have emphasized chemical defences that adversely affect the physiology of their enemies (Rogers, 1978). Resistance is due to one or more of the following mechanisms.

Antibiosis. A constituent present in the resistant variety is lethal to the insect or affects its life cycle or fertility. The resistance of lucerne to insect pests is attributed to higher saponin content, in particular medicagenic acid (Horber et al., 1974). In cotton, breeding to reduce gossypol (a toxic phenol) concentration in cottonseed to a non-toxic level for ruminants, has made the low-gossypol varieties susceptible to ten different insect pests (Pathak and Saxena, 1979).

Preference or antixenosis (Kogan and Ortman, 1978). Certain plant characteristics may repel insects, or may prevent oviposition, feeding, or the establishment of the insect (Moseman, 1966). Growing hairy cotton varieties has almost eliminated jassids as a major cotton pest in tropical Africa. *Gossypium tomentosum* has no nectaries, and attracts far fewer insects than do other cotton species; in particular, it reduces populations of *Lygus*, *Heliothis* and pink bollworm in cotton (Jenkins, 1981).

In cotton, cultivars resistant to the boll weevil carry a trait known as 'frego' bract; the female insects oviposit less eggs on a given cotton flower, because they keep

moving about on the plants, and therefore produce less progeny (Mitchell et al., 1973). Susceptibility to other pests, such as *Lygus* and fleahoppers is however increased (Maxwell, 1977).

Certain maize varieties have resistance to corn earworm, attributed to tight kernel husks, which confine the larvae longer in the husks, promoting cannibalism among the larvae (Painter, 1958).

Wheat varieties with solid stems are resistant to the sawfly: the eggs become desiccated and the movement of emerging larvae is restricted (Wallace et al., 1973).

Field resistance or tolerance. This is the ability of the plants to recover rapidly without excessive damage, after an attack.

Permanence of resistant cultivars

Several factors influence the length of time a variety can maintain its resistance (Jenkins, 1981):

- The number of biotypes in the original insect population.
- The type of resistance mechanism: antibiosis has the disadvantage of being very effective! It places an intense selection pressure upon the relevant insect population, resulting in the appearance of many resistant biotypes. For example, after the introduction of thrips-resistant lucerne varieties, many aphid biotypes appeared, so that a succession of varieties has been required to maintain sufficient resistance to enable production of lucerne in areas in which the aphids are a serious pest.

When resistance is based on antixenosis or tolerance, selection pressure is much less severe than with antibiosis, and it takes longer for resistant biotypes of the insect to appear.

The inclusion of low-level resistant varieties within an integrated control programme may enhance the usefulness of an otherwise relatively ineffective defense mechanism when used as the only method of control. The low level of resistance may still cause a lengthening of the time required to build up insect population to an economically damaging level (Jenkins, 1981).

- Other factors that influence the permanence of resistant varieties are: the type of insect reproduction; the number of insect generations per year; the host range of the insect; insect migration between generations.

Lethal genes

Methods of genetic selection used to improve plants and domestic animals, can serve to introduce lethal genes or characteristics with low survival value into insect populations (Moseman, 1966).

Breeding achievements

Breeding of crop plants for insect resistance has become a significant factor in insect

control, as evidenced by expanded programmes in maize, lucerne, soybean, wheat and cotton. In some cases, resistant varieties are the major means of insect control; in other cases, they have become an important element in integrated control (see below) (Jenkins, 1981).

In general, the insect–host relationship is far less specific and far more complex than is the case with pathogens (Beck, 1965). Notwithstanding the difficulties, a significant number of resistant varieties of different crop plants have been developed, as indicated by the following examples (Jenkins, 1981).

Maize: Hybrids resistant to the European cornborer (*Ostrinia nubilalis*) are in current use; inbred lines that show resistance to the southwestern cornborer (*Diatraea grandiosella*) have been released to experiment stations; breeding lines have been developed with resistance to the fall armyworm (*Spodoptera frugiperda*).

Wheat: One of the earliest achievements in breeding for insect resistance was the development of wheat varieties resistant to the Hessian fly (*Mayetiola destructor*); as a result, this formerly major pest has become of minor importance; breeding efforts are proceeding for resistance of wheat for greenbug (*Toxoptera graminum*) and cereal leaf beetle (*Oulema melanopus*).

Cotton: Jassid (*Empoasca* spp.) resistance, developed in South Africa in the 1930's, was the first successful effort in breeding varieties resistant to a cotton pest. More recently, sources of resistance to spider mites (*Tetranychus urticae*) have become available.

Research is proceeding on resistance to bollworm (*Heliothis* spp.); pink bollworm (*Pectinophora gossypiella*); and *Lygus* bugs.

Lucerne: The spotted alfalfa aphid (*Therioaphis maculata*) was introduced accidentally into the USA in 1954, and caused major crop losses. A considerable research effort led to the development of a number of resistant varieties, many of which have multiple pest resistance combined with high forage yields (Nielson and Lehman, 1980).

Physical control methods

Traps

Light, sound, or chemicals, may serve as lures for attracting insects to traps. Thousands of insects species, in particular nocturnal fliers, are attracted to light, and many types of traps have been devised. The traps generally consist of a lamp mounted above a collection device in which the insects are killed by a suitable volatile insecticide. Whilst conspicuous successes in insect control by these means in the field have not yet been recorded, the method may be of special interest when combined with the application of chemosterilants to the captured insects. Following capture and treatment, the insects are freed to rejoin the natural population (Henneberry and Howland, 1966).

Electromagnetic energy

Radio frequency (RF). Electric fields have been successfully used for the control of insects attacking stored grain, which cause considerable damage in the warm dry regions. Complete mortality of adult rice weevils (*Sitophilus oryzae*) has been achieved by using RF treatments for a few seconds to raise the grain temperature to about 38°C. As temperatures of this order would not normally be lethal to insects, even if applied for longer periods, it is supposed that the insects selectively absorb energy at a faster rate than the grain which they are infesting (Nelson, 1967).

Infra-red energy. This has been studied for the possible control of the pea weevil (*Bruchus pisorum*) in stored pulses, and of granary weevils (*Sitophilus granarius*) in stored cereals (Tilton and Schroeder, 1963).

Ionizing radiation. For insect control in grain, this is also receiving much attention (Cornwell, 1966).

Photoperiodic effects

It has been observed that exposures to light as brief as a photoflash, during a critical time in the normal dark period, can upset the lifecycle of an insect. This opens up new possibilities of insect control, by forcing insects to bypass their normal diapause under field conditions. Daily exposures of a few minutes to red and infra-red light were also found to inhibit the normal development of certain insects (Barker et al., 1964).

Ultrasound

Experiments have shown that bat-like ultrasound in the field reduced infestation of sweet corn by the European cornborer by more than 50% (Belton, 1962).

*Integrated control**Failures of conventional methods*

By the mid-1950's, it was becoming clear that chemical control of insects was not only becoming ineffective, but creating problems such as resistance, resurgence, and outbreaks of secondary pests. In addition, health hazards to farm workers from the poisonous sprays and to consumers from toxic residues made a search for new approaches to insect control imperative.

For example, in the 1960's, farmers in the Rio Grande Valley of Texas switched to organophosphates for controlling boll weevils that had become resistant to chlorinated hydrocarbons and carbamates. This made the situation with *Heliothis* spp. even worse. Breakdown of the control system came in 1967 and 1968 when it was found that the bollworm had become resistant to the organophosphates as well. Even 20

sprayings in a season were no longer effective. Either an entirely new solution had to be found, or cultivation of cotton in the Valley would have to cease (Perkins, 1982).

Combining control techniques

Experience had shown that the genetic plasticity of insect populations made it likely that they could evolve resistance to any single technique that might be devised, hence the idea of combining one or more techniques for an integrated control system in which "each individual method could synergise the effectiveness of the others" and "preclude the emergence of resistance in the target pest population" (Perkins, 1982).

A basic premise on which integrated control is based is that pest control is an activity that can alter the entire ecosystem, with beneficial or deleterious results. Therefore "techniques should be harmonized in an organized way into a multi-faceted flexible system" (Chant, 1966) combining chemical, biological, cultural, and genetic methods, so as to maximize beneficial results and avoid deleterious effects.

Components of integrated control

Integrated control consists of a number of essential components (Perkins, 1982).

Economic thresholds. Control measures should be taken only when the insect population density approaches the *economic threshold*, i.e., a population density sufficiently high to cause crop injury equal or greater than the cost of controlling the pest.

The lowest population density at which the rate of damage to the crop exceeds the cost of controlling the pest is called the *economic injury level*; it is different for different crops, areas, seasons, and cost fluctuations. When the economic threshold is reached, control measures have to be initiated in order to prevent the pest population from increasing to the economic injury level. The economic threshold has to be lower than the economic injury level in order to permit sufficient time for control measures to be applied and to take effect (Fig. 18.4).

When a pest population, responding to favourable environmental conditions, approaches the economic injury level, insecticides are usually the only control method that can act quickly enough to prevent a population build-up that will cause serious damage to the crop (R.F. Smith and Van den Bosch, 1967). For example, the bollworm *Heliothis zea* attacks, among other crops, lucerne (alfalfa), cotton, and sweet corn, in California. In lucerne, the population never reaches a density which causes economic damage. In cotton, the economic threshold is four worms per 100 plants, and cotton fields usually require one or two sprayings during the season to control this bollworm. In sweet corn, the market demands, for human consumption, ears that are entirely free from worms, so that the economic threshold in this case is at zero level. For this reason, insecticides may have to be applied at three-day intervals. The economic threshold may be somewhat higher when demand considerably exceeds supply (Stern, 1965).

Knowledge of the economic threshold for each crop and pest, at which insect

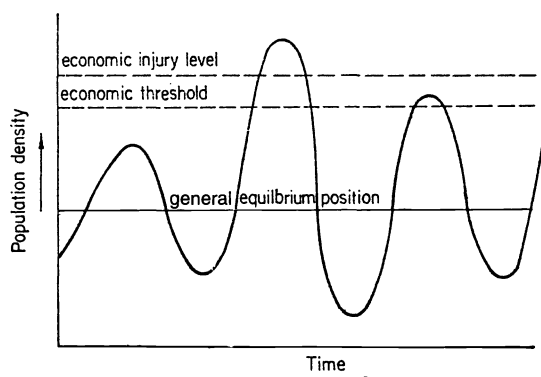


Fig. 18.4. Schematic graph of a theoretical arthropod population over a period of time, indicating its general equilibrium position, economic injury level, and economic threshold. After Stern (1965). By permission of the Food and Agriculture Organisation of the United Nations.

damage can no longer be tolerated, is essential to the success of an integrated control system; otherwise, matters may get out of control and serious damage be caused to the crop. However, it is not easy to determine these thresholds, because of the large number of factors involved and the everchanging economic and environmental conditions (Chant, 1966). An understanding of the interactions in the ecosystem is also essential (Moseman, 1966). Refraining from panicking and applying chemical control measures prematurely, requires a high degree of self-control on the part of the farmer, and confidence in the advice and instructions given by the research and extension workers. Precipitate action will result in a disruption of the whole programme.

When once the pest is reduced to an acceptable level, chemical control is stopped. The proper timing of chemical control reduces the danger of replacing one pest with another, of creating resistance to pesticides, and of eradicating beneficial insects; at the same time, it makes possible considerable savings, by drastically reducing the number of sprayings required. Chemical control of insect pests will continue to be an essential element in any control programme.

The chemical pesticides to be used in an integrated control system should preferably have the following characteristics (Cole, 1966):

- (a) Lack of residual effect; by breaking down rapidly into harmless substances, the selective pressure for the pests to evolve resistant strains is reduced to a minimum, and the problem of residues toxic to humans and disruptive of the ecosystem is also avoided.
- (b) High specificity, so that only the pest which is under attack is controlled. This will avoid harm to the natural enemies of the pest.

These characteristics are the diametric opposites of those of the insecticides that were

previously considered the most successful, such as DDT, which has a broad spectrum of effectiveness and long persistence (Moseman, 1966).

Integrated control also refers to other planned combinations of control methods, such as “harmonizing techniques in an organized way into a multifaceted flexible system” (Chant, 1966). For example, pesticides are very efficient when the insect population is high, and inefficient when it is low. The release of sterile males is inefficient at high population densities and efficient at low densities. Accordingly we see the value of ‘integrated control’, which combines the chemical and biological approaches (Ordish, 1967).

An example of successful integrated control is that of the spotted alfalfa aphid (*Therioaphis maculata*), a pest which was introduced into California from the Middle East and threatened the entire lucerne industry. It was reduced to minor status, within six years, by the introduction of two parasites, the development of resistant varieties, harvesting by strip cutting methods to preserve predator and parasite populations, and the occasional use of a selective systemic insecticide (Stern, 1965).

Protection of natural enemies. The most important conservation factor within control of the farmer is to adjust spray programmes so as to cause minimum damage to the natural enemies of the pest to be controlled. This can be done by (a) choosing insecticides that are selective and as far as is possible, short-lived and non-persistent; (b) they should be used only when necessary to prevent unacceptable economic damage (cf. p. 856), and only the minimum amount needed (Sailor, 1979); and (c) treatment of selected areas to leave reservoirs of natural enemies.

Supervised control. Supervised control includes (a) monitoring by qualified field workers to warn farmers when insect populations approach the economic level; (b) an extension service that can give the farmers ad hoc advice on all aspects of farm management that have an impact on the size of the pest population such as crop sequence, selection of variety, fertilization, irrigation, weed control, planting dates, and harvesting dates (R.F. Smith and Reynolds, 1965).

Two different approaches to integrated control evolved subsequently, called, respectively, ‘integrated pest management’ and ‘total population management’ (Perkins, 1982).

Integrated pest management

The fundamental premise on which integrated pest management (IPM) is based, is that complete eradication of a pest is neither necessary or even desirable. The development of an integrated control system requires the continued existence of pest populations, albeit at a low density. This is known as the ‘dirty-field principle’, and is an essential condition for the permanence of a balanced system of pests and natural enemies. The presence of the insect pest, when maintained at a certain level, does not cause economic damage (Chant, 1966).

The inclusion of varieties with lower levels of resistance into an integrated control programme may considerably enhance its effectiveness, and at the same time delay the appearance of pesticide-resistant insects by reducing selection pressure on the insect population.

The control of the spotted alfalfa aphid (*Therioaphis maculata*), is an example of integration of suppressive measures into a system for managing an important insect pest.

The methods for control include (Klassen, 1979):

- sowing resistant cultivars;
- treating seed with phorate or disulfoton; establishing imported parasites, *Praon pollitans*, *Trioxys utilis*, and *Aphelinus semiflavus*;
- strip cutting for the conservation of indigenous natural enemies, such as lady beetles, syrphids, *Chrysopa*, etc.
- using systemic insecticides: demeton or mevinphos.

Another example is that of the control of the pests of cotton in the Canate Valley of Peru (Barducci, 1965). The early cotton pests in this region – leafworm (*Anomis texana*), bud weevil (*Anthonomus vestitus*), cotton aphid (*Aphis gossypii*), minor bollworm (*Moscinea peruella*), white scale (*Hemichionaspis minor*), and cotton stainer (*Dysdercus peruvianus*) – were controlled by natural predators and parasites, hand collection of insects and damaged squares, and spraying with arsenical insecticides and nicotine sulphate. In 1939, considerable damage was caused by another bollworm, *Heliothis virescens*. Attempts to control this pest by insecticides caused a build-up of *Aphis gossypii*. The problem became worse from season to season and culminated in crop failure in 1949.

A new policy was subsequently adopted, using early-maturity varieties, crop rotation, and fixed dates of planting. The growing of ratoon cotton was prohibited. Synthetic organic insecticides (DDT, BHC, and toxaphene) were used and gave good control during the first three years. Yields were good. However, as the effectiveness of the above-mentioned insecticides declined, they were replaced by others, including aldrin, dieldrin, endrin, and parathion. The rates used increased progressively, the sprays were applied at shorter intervals, and mixtures of insecticides were used. After a short period, leafrollers (*Argyrotaenia sphaleropa* and *Platynota* spp.), the major leafworm (*Pseudoplusia rogationis*), the citrus mealy-bug (*Planococcus citri*) and the cotton leaf perforator (*Bucculatrix thurberiella*), became serious pests. The situation continued to deteriorate, and culminated in a complete crop failure in 1956. It was then decided to adopt an integrated control programme: synthetic organic insecticides were almost completely banned, being replaced by arsenicals and plant-derived insecticides, tillage of dry soil to destroy pupae of *Heliothis*, and other adapted cultural practices – among which repopulation with predators and parasites imported from other regions, and destruction of crop residues, were the principal measures

adopted. After seven years of integrated control, the insect problems were overcome, and yields were on the increase.

Total population management

Total population management (TPM) is an insect control strategy developed alongside integrated pest management (IPM), discussed in the previous section. Both approaches use appropriate packages of integrated techniques; the major difference between the two is that TPM aims at the complete eradication of a pest, whilst a basic tenet of IPM is that complete eradication is neither necessary nor even desirable, except in specific cases, when a target insect is distributed over limited areas of land (Perkins, 1982).

One example of TPM is the three-year programme of a carefully integrated set of techniques adopted by the Pilot Boll Weevil Eradication Experiment 1971–1973. This included:

First year:

- insecticides during the growing season;
- reproduction–diapause control: suppression of wintering population of boll weevils through insecticide application at end of season;
- chemical defoliation after harvest, to deprive the boll weevils of food, so as to prevent diapause;
- stalk destruction in autumn, to deny boll weevils a wintering haven.

Second year:

- pheromone traps in the spring, to monitor populations and destroy boll weevils;
- trap crops, consisting of a few rows of cotton planted two weeks before the second-year's crop and treated with a systemic insecticide, to destroy the first weevils that emerged from wintering;
- early season insecticide treatment when cotton flower buds were the size of pin-heads, i.e., before the boll weevils were actually damaging;
- release of sterile males so as to block reproduction in the field.

The number of adult boll weevils per hectare in the test area dropped from 2017 to 0.5 between 1971 and 1973 (Hardee and Boyd, 1976).

The pilot project indicated that eradication was a possibility, even though it had not been fully achieved; the main reason for this was probably the need for an additional year of treatment, which was not possible in the case of the pilot project because of budgetary limitations and inter-agency problems between the partners in the enterprise.

In the case of a pilot project, infestation from surrounding areas is practically inevitable.

For the control of newly introduced or newly established pests, eradication is

usually the preferred strategy. Success requires early detection and an adequate technology. If detection comes late, the pest becomes well established, and eradication may no longer be economically justified or technically feasible (Spears, 1979).

Modelling

Mathematical models of insect population dynamics can improve understanding of how crop plants, pests, and natural enemies interacted. Numerous models have been published, and the theories on basic ecology derived from them have served as a foundation for strategies of integrated pest control developed in recent years (Perkins, 1982).

Insect control in developing countries

Generally, pest control is a relatively late input, that is fairly easily adopted by Third World farmers after other innovations, such as improved varieties and fertilizers are in use, mainly because the efforts and costs already invested are otherwise likely to be lost. The disappearance of insects and other pests after chemical treatment is usually spectacular, and the good results are immediately apparent.

The environmental and other hazards involved in the use of insecticides described in a previous section are essentially the same in all countries, whatever their stage of development. However, for Third World countries, the apparently obvious solutions outlined above present intractable problems.

Firstly, the stable insecticides play a major role in the control of important disease vectors; secondly, the non-persistent insecticides are much more expensive to buy, so that only a minority of farmers at best can afford their use. Thirdly, the high toxicity to man and animal of many of the most common organophosphates makes them extremely dangerous to use. This danger and the requirement to adopt integrated control methods require a level of sophistication that the majority of farmers have not yet attained. Finally, much location-specific research in developing countries on integrated control needs to be carried out before effective methods can be proposed for adoption.

The initiative for pest and disease control cannot, as a rule, be left to the individual farmer – especially if he is still lacking in experience of modern technology. Firstly, he may fail to identify the pest or disease and be unaware of the appropriate control methods. Secondly, even if he does effectively control an outbreak in his own field, he will frequently have wasted his efforts and money if his neighbours neglect to do the same. Thirdly, there appears to be a rather significant difference in the speed of adoption of pesticides between larger and smaller farms. This is apparently due to the greater complexity in the use of these chemicals, as compared to new varieties or fertilizers, and to the highly toxic nature of many of the chemicals used (Gotsch, 1973). And, fourthly, after relatively short periods, simple chemical control treat-

ments frequently become ineffective and must be replaced by more sophisticated approaches.

Accordingly, there is a need for the creation and maintenance of an efficient crop protection service as one of the first essentials of agricultural development. This service will have to forecast insect invasions and disease epidemics whenever possible, advise the individual farmer on appropriate measures and organize joint large-scale control measures whenever the need is indicated. Mobile groups of specially trained monitors will have to carry out a constant surveillance of the pest and disease situation within defined areas of jurisdiction.

Special equipment is also generally needed for the efficient application of fungicides and insecticides; this cannot be provided by individual small farmers.

Problems of supply

The developing countries are almost entirely dependent on imports of pesticides. Those most in use are the broad-spectrum pesticides (e.g., aldrin, dieldrin, DDT) which, besides being extremely effective for a large number of pests, are also by far the cheapest to produce. However, in recent years, legal restrictions on the production and use of these pesticides in the developed countries (because of their negative effects on the environment) have caused supply shortages and have pushed prices up drastically (FAO, 1976).

Future production in exporting countries will be geared to the needs of developed countries, namely, target-specific and non-persistent pesticides, which are expensive and require sophisticated methods of application. Developing countries will therefore be doubly affected: not only by the shortage and high cost of the customary pesticides, but also by the neglect in developing new plant protection chemicals suitable for crops and conditions in developing countries, because of the small and uncertain markets (FAO, 1976).

Improving the adoption of pesticides

FAO recommendations for improving the adoption of pesticides in the developing countries include (FAO, 1977):

- (a) better formulation of pesticides suited to tropical conditions;
- (b) more adequate standards and uniform methods for controlling the chemical, physical and biological properties of the products sold to farmers;
- (c) establishment of local formulation facilities where raw materials are available; and
- (d) promotion of more efficient and safer use of pesticides at farm level, in particular using units that are simple, easy to operate by hand and suitable for small farms.

Many countries have developed, or are developing legislation relating to these matters. However, legislation cannot be effective until inspection services are organized, technical facilities established and personnel trained and appointed to enforce regulations.

Spider mites

Description

The spider mites (Tetranychidae) are small, green or red soft-skinned organisms with a chitinous skeleton. They differ from insects in having four pairs of legs, and in that no part of their body is differentiated into a head. They often construct cobwebs, under which they live (Kranz et al., 1977).

Economic importance

The spider mites are an economically important group of the order Acarina which causes severe losses in many important crops. Spider mites damage leaf surfaces and inject toxic substances into the plants. Yields are greatly reduced, and plants may be killed outright. Injury is particularly severe in hot, arid environments, in which they reproduce throughout the year and give rise to a considerable number of generations.

The spider mites' importance as a major pest has increased considerably since World War II, mainly as a result of improved plant nutrition, which increases the fecundity of the mites feeding on the plants. The increased use of pesticides, which have reduced the natural enemies of the mites that formerly checked their populations, also played a role (E.H. Smith, 1979).

Control

The spider mites are generally controlled with acaricides. The same acaricide should not be used too often in succession, in order to prevent a build-up of resistance. Biological control in California is based on a predatory mite (*Phytoseiulus persimilis*), and in Hawaii, using another species (*P. macropilis*) (Kranz et al., 1977).

P. persimilis is successfully used in the glasshouses of Europe and America for controlling red spider mites on various vegetables, roses and other ornamentals (Van Lenteren and Woets, 1988).

Control methods include cultural practices, biological control, breeding for resistance, chemical control by acaricides, solar soil sterilization.

Nematodes

Economic importance

Nematoda constitutes one of the most numerous groups of animals in the world. It includes free-living predators and beneficial species living in the soil (cf. p. 467) and in water, and feeding on plant and animal detritus, and on micro-organisms. It also includes many species of plant parasites, some highly specialized, others capable of attacking many plants.

Nematodes are found in soil and water throughout the world, even in deserts. Almost any soil contains several species of nematodes, including parasitic species. Plant nematodes are found wherever host roots occur, even to a depth of 5 m, but they are most abundant in the 30 cm top soil.

All plants are susceptible to attack by one or more nematode species (Feldmesser, 1979). It is only since World War II that the economic importance of the damage caused by nematodes, as parasites of major crops, has been fully recognized and studied.

In developing countries, the problems caused by nematode infestation, which affects almost all export crops and many food crops, have been largely neglected and frequently unnoticed. Trees and shrubs serve as reservoirs for extremely harmful nematodes that can thereby survive the dry season and high temperatures to which parasitic nematodes are most susceptible (see below). For example, the baobab (*Adansonia digitata*), a widely distributed tree in the Sudo-Saharan zone, serves as a host to the extremely harmful nematode species *Meloidogyne* spp. and *Rotylenchus reniformis* (Van Gundy and Luc, 1979).

Some nematode species are potentially useful agents for biological control of certain insect pests and weeds.

Parasitic nematodes

Parasitic nematodes are differentiated into root nematodes, stem nematodes and leaf nematodes (Kranz et al., 1977).

The most important parasitic nematodes are those living on and around roots (ectoparasites) or inside roots (endoparasites). The root sedentary endoparasites include some of the most harmful plant parasites: the *cyst nematodes* (which attack sugar beet, crucifers, bean, lupine, vetch, clover, potato, tomato, oat, wheat, rye, tobacco) and *rootknot nematodes*, which affect a still wider variety of plants (Feldmesser, 1979).

Nematode damage to the roots affects root functioning, resulting in chlorosis, mineral deficiencies, wilting (even when soil moisture is adequate), stunted growth and low yields. The nematodes are also vectors for many virus diseases.

Nematodes form complex interactions with other organisms. They may parasitize nearly all plants and animals, insects, fungi, bacteria, and other nematodes. They can interact with other plant pathogens, transmitting virus diseases, opening infection sites, or reducing their hosts' resistance to other diseases.

Various species of nematodes form synergistic complexes with fungi; for example, several *Pratylenchus* species form such complexes with wilt fungi, such as *Rhizoctonia solani*, *Fusarium* spp. and *Verticillium* spp. or *Meloidogyne* spp.

Such complexes can cancel the resistance of a plant to fungal pathogens, or, alternatively, make plants susceptible to otherwise saprophytic fungi (Kranz et al., 1977). Nematodes thereby increase the severity of many plant diseases, in particular those that are soil borne (Rebois, 1979). The very important ability of the plant to take up water and nutrients is thereby impaired.

General characteristics

Nematodes, with their long, thread-like and transparent bodies, mostly live on micro-organisms or as predators, others are parasites of man, animals or plants.

Most plant parasitic nematodes are about 1 mm long; they are equipped with a buccal stylet with which they puncture cell walls and suck out sap, whilst injecting salivary secretions into the cell. The secretions contain toxins, which may kill the cells rapidly; also hormones and enzymes which stimulate growth of the infected cells and increase their nutrient content. In the case of virus-carrying nematodes, the plants are infected with the disease. The small wounds may also enable penetration of the plant tissues by fungi or bacteria.

Mature females usually become sedentary, whilst adult males of all species are worm-like and motile.

Migratory nematodes lay their eggs individually or in clumps in the soil, roots, or other plant tissues. Sedentary nematodes lay their eggs in a gelatinous egg matrix outside the body, or retain them within the body (cyst nematodes). In the latter case, as the female matures, her cuticle forms a hard, leather-like protective covering, called a cyst, which protects the eggs and developing larvae for long periods.

The roots of host plants excrete substances which cause dormant nematode eggs to hatch; the emerging larvae are attracted to a nearby root which they penetrate.

Environmental factors

Nematodes are the most abundant multicellular organisms in the soil (Kranz et al., 1977). Soil conditions which affect nematode population dynamics are: temperature, moisture, soil type and structure, pH, atmosphere, root exudates, availability of a suitable host, cropping sequences, and competition from other soil organisms (Rebois, 1979).

The optimum temperature for motility, infectiveness, development, and reproduction is between 15 and 30°C; in dry and warm regions it is nearer to the upper limit. The cysts can withstand great temperature extremes.

Optimum conditions for nematode development and infection prevail when soil moisture is just below field capacity: oxygen and carbon dioxide exchange is efficient and the available moisture facilitates nematode movement through the soil.

Under irrigation, the warm moist soil provides such optimum conditions, and the lifecycles of most plant-parasitic nematodes take from three to six weeks. They can therefore multiply at a rate of five to ten generations a year and can cause extensive damage. Conversely, drying the soil, and exposing live nematodes to direct sunlight, kills them rapidly.

It follows therefore that nematode development and infectivity are severely curtailed under dry conditions, and that a change from rainfed to irrigated farming will considerably increase nematode infection.

Though nematodes are unable to parasitize roots effectively in dry soils, they may survive, as cysts, periods of desiccation that may vary, according to species, from a few weeks to many years.

Active soil and plant nematodes are basically aerobic and become quiescent or die in waterlogged soils. Because extreme conditions are unfavourable for nematode development, drying the soil, or, alternatively, flooding are recommended as control measures. However, as many nematodes can survive as cysts long periods of dryness, and others have adapted to life in rice paddies, the efficacy of these measures is limited.

The movement of nematodes in the soil is extremely slow; greatest dispersal of the pest is due to Man's activities: irrigation, use of infected implements and equipment, poor nursery sanitation, infected planting material, etc.

Species

The four major species of plant parasitic nematodes are: rootknot nematodes, root lesion nematodes, stem nematodes and stubby root nematodes

Rootknot nematodes (*Meloidogyne* spp.) parasitize over 3000 plant species, including all major economic crops. Of the more than 30 species known to parasitize plants, the four most widespread and damaging in the dry, warm regions are: *M. incognita*, the economically most important, which is possibly a complex of several related species; it causes considerable damage in hot climates to over 700 host plants; *M. javanica*, which occurs mainly in tropical and semi-tropical regions; this species also has over 700 known hosts; *M. arenaria*, which is widely distributed in hot climates; and *M. hapla*, which is widespread in the temperate regions, but is found only at high altitudes in hot climates.

The rootknot nematodes are endoparasites that cause the formation of galls on the

roots; these contain one or more females in various stages of development; the females swell up, and can then no longer leave the gall. The shape of the gall varies, according to nematode and plant species.

Physiological changes in the affected roots reduce their ability to absorb water and nutrients and the plants are therefore more sensitive to moisture deficiencies. They may wilt and show symptoms of nutrient deficiencies even when ample moisture and nutrients are available. Affected plants are also weakened by the withdrawal of food, and assimilation by the leaves is reduced. Consequently, growth is stunted, foliage becomes yellowish, yields are considerably reduced, and the quality is impaired (Kranz et al., 1977).

Root lesion nematodes (*Pratylenchus* spp.) are migratory root nematodes, all stages of which can penetrate or leave the roots. Reproduction takes place in the roots. In contrast to rootknot nematodes, which stimulate host cells to grow, root lesion nematodes kill the cells on which they feed. Necrotic sites arise in infected parts of the root, and root rot can result from secondary invaders. Above-ground symptoms are similar to those caused by rootknot nematodes.

Stem and bulb nematodes (*Ditylenchus*) predominate in temperate regions, but certain species are pests in low-latitude warm regions. For example, the rice stem nematode (*Ditylenchus angustus*) is a major pest, common in rice-growing regions of Asia and Africa.

When the above-ground parts of the rice plant are covered with a film of water, the nematodes migrate upwards from the soil, and penetrate the growing point of the plant. Later, they move to leaf sheaths, stalks, peduncles, panicles and young seeds (Kranz et al., 1977). Leaves become whitish green, twisted, and deformed; the panicles become distorted and part of the seeds are deformed and sterile. Plant growth is retarded, and yields may be reduced as much as 90% (Kranz et al., 1977).

Under dry conditions, the nematodes coil up on ripening plants and show no sign of life. If moistened, they quickly regain their full mobility. Towards the end of the growing period, they form cottony masses on the drying plants and on the stubble; in this state they can survive drought for six months and more.

Stubby root nematodes (*Trichodorus* spp. and closely related *Paratrachodorus* spp.) are typically ectoparasites, that live in the soil and feed on root tips and destroy the growing point. The nematodes seldom kill the host plant, but weaken it by damaging the root system; affected plants are stunted and chlorotic, and wilt rapidly when moisture-stressed. Warm-region crops that are attacked include maize, soybean, cotton, sugarcane, tomatoes and citrus.

Control

It has been pointed out above that nematodes are involved in many disease complexes; often, especially in the case of facultative parasites, controlling the nematode

controls the disease complex. It is often more economic to control the disease complex indirectly by fumigants or nematicides than directly by fungicides or antibiotics (Rebois, 1979).

Many of the soil-inhabiting nematodes fulfill useful roles; control measures therefore should be specific and directed, wherever possible, at harmful species.

Nematodes are most vulnerable to control methods when they are in the active stage. More than 200 times as much active ingredient of a nematicide is required to kill the egg masses of a rootknot nematode than to kill free-living, second-stage larvae (Rebois, 1979). Control is therefore most effective when environmental conditions are optimal for nematode activity.

The cyst nematodes are especially difficult to control by chemicals or crop rotation, because eggs and larvae are protected in the dead female bodies within a sack-like skin, forming a resistant container (cyst) within which they remain viable for long periods.

The major control methods are:

- Nematode-free planting material: for most species, 52°C moist heat is the thermal death point, and is the temperature generally recommended for hot waterdips for killing nematodes in living plant material.
- Choice of planting date to give the crop a head start over the nematodes. For example, early spring planting of sugar beets will impede the attack by nematodes because of sub-optimal temperatures for the pest.
- Breeding for resistance: gradations from completely resistant to susceptible strains are common for many cereal and vegetable cultivars.

About 150 nematode-resistant cultivars have been bred in the USA since the 1950's in cotton, soybean, various forage legumes, tobacco, various vegetables and fruit trees. In resistant plants, the penetrating nematodes are rapidly encapsulated by necrotic cells which form as the result of a hypersensitive reaction of the root cortex and endodermis (Kranz et al., 1977).

The main limitations of resistant cultivars are: (a) resistance is generally confined to a single species of nematode, while in most agricultural soils, two or more species reduce crop yields; (b) resistance is also rapidly developed by mutant nematode strains. Notwithstanding these drawbacks, resistant cultivars are a major means of controlling plant parasitic nematodes (Hanson et al., 1979).

Crop rotations are used for susceptible crops, for which control methods applicable for high-value crops are economically unjustified. Many non-host plants produce exudates that stimulate hatching of nematode eggs. For example some of the Cruciferae and Chenopodiaceae provoke hatching of *Heterodera shachtii* eggs, but are not hosts to the larvae (Curl and Truelove, 1986).

In the absence of host plants, host-specific nematodes starve; for these parasites, rotations including suitable non-host plants are very effective. However, for nema-

todes with a wide range of hosts, such as the rootknot nematode, the choice of non-host crops is very limited, and becomes even more so, when several nematode species are present.

Trap crops are host crops sown in order to attract nematodes and are then harvested or destroyed before the nematodes are able to hatch (Palti, 1981). The leguminous herb *Crotalaria spectabilis* has a suppressant action on rootknot nematodes (McNew, 1966).

Biological control: certain bacteria, fungi, protozoa, and insects attack and destroy nematodes; certain fungi, in particular, are able to trap nematodes, either by powerful adhesives which they produce, or by forming rings around their prey (Eren and Pramer, 1978). Their potential as biological control agents is being investigated, but few attempts have been made at commercial exploitation of these natural enemies (Lynch, 1983). Some success in reducing nematode population was achieved with the fungus *Arthrobotrys conoides*, but four weeks after treatment, the nematodes had returned to their original numbers (ibid.).

Antagonistic plants actually kill nematodes that penetrate their roots; marigold, for example, controls root lesion nematodes (Taylor, 1979).

Soil fumigants and solar heating: the methods applied for soil-borne diseases are also effective in controlling nematodes (cf. p. 899). *Meloidogyne* species serve as test organisms for evaluating the effectiveness of nematicides. It is often possible to treat only the row; this provides a band of nematode-free soil in the vicinity of the seedlings, and gives the crop a good start (Barrons, 1979).

Non-fumigant nematicides have been developed, which can be incorporated in the soil before or during planting, or applied dissolved in water.

Molluscs

Snails and slugs are controlled by molluscicides. Several carbamate insecticides are active against snails, but metaldehyde is a specific attractant and toxicant for snails.

Aquatic snails are a major health hazard in many warm countries (cf. p. 426) and trialkyltin derivatives are effective for their control. Clonitralid has significant selectivity and low mammalian toxicity (Plimmer, 1979).

Vertebrate pest control

Research on vertebrate pest control has been very limited, compared to the effort expended on other aspects of plant protection. The use of toxic chemicals to control vertebrates is very problematic; vertebrate pests are part of the food chain of many carnivores, and control of any species may have disruptive effects on ecological

balance (Isom and Worker, 1979). These workers estimate that the depredations caused by vertebrate pests may equal or exceed losses from diseases, insects, nematodes, and weeds.

Mammals

Rodents

Rodent pests include rats, mice, gophers, squirrels, porcupines, etc. They destroy crops above and below ground, and cause enormous damage to stored agricultural produce.

In dryland ecosystems, rodent populations are kept under control by the scarcity of food and pressure by natural enemies; but both constraints are removed by irrigation. Ghabbour (1977) reports that rodent outbreaks occurred in Egypt in newly irrigated areas.

Species of the genus *Rattus* are among the principal crop pests in the tropical and subtropical areas of the world. Chronic losses to crops are serious and sporadic. Outbreaks can cause severe food shortages such as those that have occurred in large areas in several Asian countries following rat population eruptions. Traditional methods of control are generally ineffective. Post-harvest losses, both direct and indirect, are also considerable.

The damage caused by mice, though less conspicuous, is also considerable.

Rodents also cause heavy damage in livestock and poultry production and are frequently involved in human and animal disease transfer. Rats alone are carriers and reservoirs of more than 50 human diseases (Kranz et al., 1977).

Other injurious mammals

The elimination of natural predators and legislation for the protection of wildlife have in many cases resulted in an increase in large herbivores that cause severe crop damage, such as antelopes and deer, which destroy crops or compete with livestock for pasture. Wild pigs and warthogs cause much damage to maize, root crops, etc. Where monkeys are numerous, they can be destructive pests, damaging groundnuts, maize, and other cereals (Kranz et al., 1977).

Control methods

Stone and Hood (1979) distinguish between *lethal* methods for population reduction and *non-lethal* methods. Both approaches may be based on chemical, mechanical, ecological, or cultural means. Most crops are vulnerable to vertebrate damage for relatively short periods; preference should be given to non-lethal techniques that discourage the animals from causing damage during these short periods. Lethal control should usually not aim at eradication, but towards reducing the populations to the level at which damage can be tolerated.

Mechanical or physical control. Exclusion procedures are the most generally useful procedures if economically acceptable. There are many kinds of devices for this purpose. Fences, including electric fences, are very effective, but expensive for large areas. Trapping animals, to kill them or move them to another location is another approach. Sport hunting or deliberate culling are widely used.

Cultural methods. Planting of crops to coincide with the availability of natural foods preferred by the animals, can reduce damage to the crops.

Chemical control. Numerous compounds have been registered for the control of mammal and bird pests; most control has been based on six poisons which are presently either banned or restricted in their use by regulations: sodium fluoroacetate, strychnine, thallium sulphate, zinc phosphide, anticoagulants (warfarin) and nitropyridine oxide (avitrol). The first four are serious environmental contaminants (McCabe, 1979).

Zinc phosphide and strychnine are fast-acting and are lethal after a single dose. Degradation of zinc phosphide is relatively rapid and it is used where a fast-acting rodenticide is required. Strychnine alkaloid is less toxic to other forms of wildlife than to rodents, but its taste and rapid onset of toxic effects may interfere with the intake of a lethal dose by rodents.

Since 1950, anti-coagulants, which cause death by internal bleeding, have been the major slow-acting rodenticides in the USA: warfarin, a coumarin compound, is widely used. Other anti-coagulants in wide use are coumaphyl, and pindone, an indadione compound. Their main advantage is that primary hazards to other mammals and to birds are limited, though there may be secondary hazards (Stone and Hood, 1979).

Another group of lethal chemicals are fumigants, such as carbon bisulphide, cyanogas, methyl bromide, chloropicrin, and carbon monoxide, mostly used in rodent burrows.

A major problem in the use of toxicants against commensal rodents, is that those animals that have ingested sub-lethal doses of the poison avoid eating more of the bait ('bait shyness').

The use of a lethal agent in an area for several years may cause selection of resistant individuals; for example, voles that were effectively controlled by endrin, eventually developed resistance to the pesticide. Rats on farms and cities have developed resistance to warfarin (Davis, 1979).

Biological control. The case of rabbits in Australia is a classic example of irresponsible introduction of animals into a new environment, in which they become a major pest, and also of the transience of a dramatically successful biological control method.

In 1859, 12 pairs of wild rabbits were introduced into Australia from England, to provide hunting to an estate owner. A hundred years later, their number had grown to an estimated 600 million, despite all the efforts made to eradicate them. The rabbits competed with livestock for forage, destroyed trees, and accelerated erosion of denuded soil. In the 1950's, the rabbit plague was brought under control by the introduction of a viral disease (myxomatosis), which wiped out 90% of the rabbit population. The rabbits developed resistance, and within thirty years, the rabbits had again reached an estimated 400 million. Efforts are currently being made to develop a new strain of the virus, as well as to release a new myxomatosis carrier flea (Time, 1991).

In the case of the Australian rabbits, both the pest and the control agent were introduced into the country. Other examples of vertebrate control by diseases, parasites or predators are rare. The introduction of mongoose into many islands to control rats has resulted only in seriously reducing species of ground-nesting birds. From a review of various attempts at biological control made over the years, Stone and Hood (1979) conclude that "the risks and problems of introducing predators appear to be greater than those with chemicals or with cultural, mechanical, or other ecological methods of damage control".

There is some potential for birth control by field baits containing female hormones, a topic subject to continuing research (McCabe, 1979). Mestranol, a synthetic estrogen, has shown promise as a sterilant for several rodent species, but rats do not readily accept the bait.

Birds

Control

Birds have considerable reproductive capacity, a wide range of diets, and mobility, which makes it difficult to achieve long-term control. Control methods include: in-flight obstacles, scaring devices, chemicals, exclusion, and the breeding of resistant cultivars.

Scaring devices. Scaring devices are *visual*, such as scarecrows, dead raptors or models of birds of prey, corpses of the pest species; *acoustic*, such as propane or carbide exploders or firecrackers, distress or alarm calls of birds being mistreated or frightened, played from loudspeakers. Some models have been developed that can be set to function only at certain periods of the day.

Scaring devices soon lose their effectiveness as birds become accustomed to them. Krebs (1980) mentions three ways in which this can be, at least partly, countered: periodic presentation (on-off), varying the site of the scarer, and reinforcement with a real danger, such as shooting.

Visual scarers may even become counterproductive, when the birds associate their presence with good feeding areas! (Inglis, 1980).

Chemical repellents. Toxic compounds, at sublethal levels, may serve as repellents. Birds, like other animals, soon learn to avoid food that makes them ill. Repellents act by 'conditioning' such aversion. Another approach is to use a chemical, such as avitrol (2,4 amino-pyridine), which causes birds to utter distress cries and fly in great panic, before dying. This method is effective with gregarious species, because only a few birds need to take the poisoned bait in order to frighten away a feeding flock of several thousand (E.N. Wright, 1980).

Probably the most effective chemical repellent is a carbamate insecticide called methiocarb, which has shown excellent potential as a broad-spectrum repellent on various field crops, vegetables and orchard crops in many countries (Stone and Hood, 1979).

Lethal chemicals. Strychnine alkaloid is used as a fast-acting lethal bait for the control of bird damage in California and elsewhere. Another fast-acting lethal chemical used in many countries is an organophosphate, phosdrin. It is extremely dangerous to non-target animals. 'Starlicide' (3-chloro-*p*-toluidine) is a slow-acting, lethal bait, specific for birds.

Another class of chemical toxicants consists of a wetting agent or surfactant, such as PA-14 or tergitol, which destroys plumage insulation by the detergents, and causes death by exposure.

Sterilants. Ornitrol is a synthetic hypocholosteremic agent used for sterilizing pigeons in urban environments.

Exclusion. Nets are used to exclude birds from valuable crops.

Resistant varieties. Breeding for resistance to bird attack has had very limited success. Sorghum is one of the most susceptible cereals to bird damage. Small, isolated fields of sorghum can be entirely destroyed. The only practical control has been to concentrate the crop in large areas, so that the percentage of the crop destroyed by the birds is economically acceptable.

Cultivars of sorghum with long and tight glumes and dark-brown seeds have been found to be bird-resistant in Arizona (Stone and Hood, 1979), possibly because of the high tannin content of the seeds. Unfortunately, because of their astringent taste, and dark colour, the grain is unattractive to human consumers. When no other food is available within a reasonable distance, even the resistant varieties may be attacked.

The case of the quelea birds

The depredations of quelea birds in East Africa are a well known example of the extensive damage that can be caused to crops by grain-eating birds. The birds congregate in enormous flocks to feed, roost, and breed. They have a vast range, and many inaccessible reservoirs for reinfestation make permanent reductions in number im-

probable (Flegg, 1980). The problem has been intensified as the result of the widespread practices of burning, deforestation, and overgrazing (Stone and Hood, 1979).

Over most of quelea's range, the semi-arid climate (three months rainy season and nine dry months) makes rainfall patterns and timing highly erratic and unpredictable, resulting in erratic migrations and attacks on cultivated crops.

Traditionally, whole villages turn out to protect the crops; this extremely labour-intensive protection measure seldom prevents damage, but spreads it out more evenly.

In the Republic of South Africa, despite massive kills by aerial spraying (with parathion and fenthion, both organophosphates), resulting in over 100 million birds killed in one year, devastation of farm crops continued. Alleviation of damage was short-lived.

The departments of agriculture in Kenya and Tanzania have established special quelea control units which combat the bird plague by aerial spraying of breeding colonies, the use of explosives and the cutting down of branches bearing nests and young birds (Bohnet and Reichert, 1972).

The FAO is conducting research aimed at controlling weavers and quelea grain-eating birds as a regional project in Africa involving thirteen nations (Sanchez, 1975).

No method of biological control is known, and Kranz et al. (1977) think it is unlikely that any will be found.

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CHAPTER 19

Plant Diseases

The risks of devastating plant disease epidemics have been considerably increased by the following man-made changes in crop ecology (Zadoks and Schein, 1979): (a) enlargement and aggregation of fields; (b) increase in the density of host plants; (c) decrease in genetic diversity of host plants; (d) increase in monoculture; (e) increase in fertilizer use; (f) increase in irrigated areas; (g) international exchange of contaminated material. Zadoks (1989) sums up the situation by stating that “whenever and wherever a crop is grown for maximum yield, after correcting the deficiencies of soil and climate by modern technology, the within-crop microclimate is suitable for the major diseases of that crop”.

Plant diseases are caused by (a) abiotic factors, which are non-infectious and comprise air, water and soil pollutants, nutrient deficiencies, etc., and (b) pathogens, that are infectious. We are concerned here only with the infectious biotic agents.

Plant diseases and aridity

The conditions that are prevalent in dry regions have varying effects on plant diseases. In semi-arid climates, summer heat and drought play a similar role to that of winter cold in temperate climates in reducing drastically the amount of inoculum in unirrigated crops, for which reason these crops are rarely attacked by highly drought-susceptible bacteria (Palti and Shoham, 1979). However, many pathogens survive the summer in a dormant state, or persist on crops grown under irrigation.

Categories

There are two main categories of pathogens from the point of view of their development under arid conditions (Rotem and Palti, 1968):

(a) *Pathogens well adapted to surviving dry spells or seasons.* These are generally weak or only moderately strong parasites, and include species of *Alternaria* and

powdery mildews. Irrespective of weather conditions, these diseases manage to develop epidemically every year if susceptible hosts are present, and are not markedly dependent on microclimatic conditions. The main influence of irrigation on these diseases is indirect, being due to its effect on the host plants and the possibility of growing them throughout the year. Techniques of irrigation have little influence on the intensity of these diseases.

(b) *Pathogens with high moisture affinities.* Pathogens belonging to this group, such as rusts, downy mildews, and *Phytophthora* spp., are generally strong pathogens, whose development is limited to specific seasons. They are greatly affected by microclimatic effects, such as dew and shade, and by methods of crop management, such as irrigation, planting density, etc. In the dry regions, conditions for a build-up of the massive quantities of inoculum required to produce epidemics are generally sub-optimal for these pathogens. As only small amounts of inoculum survive the dry spells, a fairly long period of time is required to achieve a build-up of inoculum to epidemic proportions; hence the marked time lag between the occurrence of environmental conditions favourable to the pathogen and the actual outbreak of the epidemic. One advantage of the arid regions is the possibility of growing, under irrigation, disease-free seed during the dry period.

For this category of pathogens, irrigation has a considerable effect on disease intensity, both by increasing the predisposition of the host and by the creation of a favourable environment for the pathogen. Methods and frequency of irrigation, as well as timing of the water application, have marked effects on the severity of infection.

Temperatures and air humidity

In dry climates, two factors have an inhibitory effect on plant diseases; these are high temperatures and low air humidity (Reichert, 1954).

Diseases that originate in cooler climates are adversely affected mainly by high temperatures. *Tilletia tritici* occurs in wheat only when rain and low temperatures prevail shortly after germination. Similarly, *Claviceps purpurea* is favoured by wet seasons with limited sunshine (Heald, 1933). *Puccinia graminis*, which is prevalent on wheat in lower Egypt, does not occur in the Sudan, because of the low air humidity there (Vayssi re, 1954).

Sclerotinia sclerotiorum, with an optimal temperature between 17 and 21 C, attacks plants during the winter, whilst summer crops remain healthy. Sunflower (*Helianthus annuus*), which is attacked by the disease in damp, cool climates, is practically immune when grown in a dry, hot climate (Reichert, 1954).

For pathogens originating in hot climates, it is the dryness of the air which is a limiting factor. The spores of many fungal pathogens will not germinate unless enveloped in a film of water. In hot and dry weather, the surface of leaves dries rapidly, and this prevents many disease epidemics from developing. Prevention of yellow rust

(*Puccinia glumarum*) epidemics on wheat in Israel by a few hot, dry days in the spring, when the hot winds from the desert are blowing, has already been mentioned (cf. p. 74).

The maize rusts *P. sorghi* and *Ustilago zae* attack maize in Israel only when it is grown in the vicinity of the sea or under overhead irrigation. Other maize diseases, such as *Diplodia zae*, *Sclerospora macrospora*, and *Physoderma zea-maydis*, occur in regions with frequent rains during the growing period but not in the arid regions.

In general, root and stem diseases are more prevalent than leaf diseases in arid regions (Reichert, 1954). Leaf diseases, caused by wind-borne fungi, commonly require rainfall and a high air humidity in order to spread and infect crops (McNew, 1966). There are, however, exceptions, as will be shown in the following sections.

Arid regions may also be a source of infection of important diseases. For example, black rust (*Puccinia graminis*) is a major disease of wheat in many regions. In moist, cold regions, low temperatures destroy the uredospores on wheat, so that the main remaining source of infection consists of the spores that develop on a secondary host, the barberry (various species of *Berberis*). By destroying the barberry bushes, an essential link in the lifecycle of the rust is eliminated, and rust epidemics can be prevented.

However, in warm arid regions, temperatures do not fall sufficiently to kill the uredospores produced on wheat and native grasses which continue to grow throughout the winter. These are potent sources of infestation – not only for the arid regions themselves, but also for adjacent wheat belts – causing epidemics when conditions are favourable, even in regions in which barberry bushes have been eliminated (Ordish, 1967).

Soil moisture

A high soil moisture and increased turgidity of the plants at the time of infection generally favour most air-borne diseases. However, the relationship between moisture régime and plant disease does not always follow a consistent pattern.

For example, moisture stress was found to increase susceptibility of sesame to *Alternaria* and *Corynespora* blights, probably as a result of induced senescence; the recovery of infected plants was also delayed, as compared with plants growing under conditions of adequate moisture supply (Culp and Thomas, 1964). Similarly, tobacco grown under conditions of limited moisture was found to be more susceptible to *Peronospora tabacina* than was tobacco grown with plentiful moisture. However, in this case it was found that, irrespective of the previous moisture régime, actual inoculation only occurred when the leaves were turgid, and only negligible infection occurred on flaccid leaves (Rotem et al., 1968).

A xerophytic environment favours powdery mildews (*Erysiphe* spp.) and therefore plants grown under conditions of deficient moisture are more heavily attacked than are those growing under a more favourable moisture régime (Yarwood, 1949). Pow-

dery mildew (*Erysiphe polygoni*) was found to increase in severity on red clover when this was grown under conditions of limited moisture (Curl and Weaver, 1958).

Whilst root rots due to *Rhizoctonia*, *Fusarium*, etc., may increase as a result of excess moisture, they are usually more harmful to a crop under conditions of water stress than under optimal water conditions (Menzie, 1967).

Drought stress can affect crop disease indirectly, when the plant is so weakened by an even relatively moderate moisture deficit that it becomes susceptible to drought-tolerant pathogens. *Fusarium culmorum* attacks wheat at very low soil moisture potentials, and is known to American farmers as dryland foot rot (Cook, 1973).

Effects of irrigation on plant diseases

Factors conducive to disease

In general, irrigation favours the incidence and spread of many crop diseases by its influence on macroclimates as well as on microclimates and on the soil moisture régime. It affects both the host and the pathogen. The rapid succession of crops (especially if monoculture is practiced), the longer periods that the stomata are widely open, the increased succulence of the tissues as a result of favourable moisture supply and higher rates of nitrogen fertilization, and the increased plant populations necessary to make efficient use of the favourable growing conditions, are all contributory factors that increase the susceptibility of the crop and create more favourable conditions for infection.

The greater planting densities required in irrigation farming, and the more luxuriant vegetative growth resulting from a favourable moisture régime, ensure more shade and longer periods of high air humidity under the leaf canopy and accordingly slower drying of the soil surface. These conditions are favourable for the infection of the lower leaves and root collars of field crops, which effect is especially marked in the case of *Cercospora personata* on peanuts (Rotem and Palti, 1968). Occasionally, however, the improved vigour of the crop plant due to a favourable moisture régime will increase its resistance to disease.

The increased vigour can also help crops attacked by pathogens, such as rootknot nematodes (*Meloidogyne* spp.) that do not develop rapidly, to reach maturity in spite of infestation (Palti, 1981).

By changing the microclimate and often to some extent also the macroclimate, irrigation affects the viability of air-borne spores and may favour spore dispersal; it may also increase the speed with which the infection is spread (Rotem and Palti, 1968).

Fluctuations in soil moisture are inevitable in all irrigation methods, excepting trickle irrigation (cf. p. 599). If a policy of frequent irrigations, applied at low rates, is adopted, shallow root growth will be promoted. As the top soil dries out quickly, plants will be stressed towards the end of the interval between irrigations, and pathogens, such as *Fusarium* wilts may take advantage of the situation (Palti, 1981).

Irrigation promotes the growth of weeds, and thereby contributes to the survival and increase of inoculum. Gerechter-Amitai (1973) has shown that cereal weeds transmit cereal rusts.

The interrelation between irrigation and plant diseases is complicated by the interactions of a number of factors affecting the time and extent of disease development in irrigated crops. Some of these factors are (Rotem and Palti, 1968):

- (a) weather: rain, air humidity, temperature, radiation;
- (b) pathogen characteristics: time of spore dispersal, drought resistance of the spores, speed of infection;
- (c) method of irrigation used, frequency of irrigations, and time of day at which water is applied; and
- (d) cultural practices specific to irrigation farming.

However, the most important effect of irrigation on diseases is the absence of a dry period during which inoculum development is inhibited, the so-called 'drought incision' (Palti, 1981). Where double cropping can be practised, as is the rule in irrigation farming, whether of the same crop (e.g., rice), or two crops susceptible to the same disease (e.g., wheat and maize), inoculum increases to a considerable extent.

The following examples illustrate the relationship between irrigation and plant disease:

Certain diseases, and in particular those caused by downy mildews, are especially favoured by the young and succulent growth promoted by irrigation. Examples include the increased incidence of downy mildew of peas and lucerne (Rotem and Palti, 1968), and of *Sclerospora graminicola* on pearl millet (Kenneth, 1966).

Sclerotium rolfsii, which attacks many crops, requires a combination of high temperatures (30–35°C) and favourable soil moisture conditions (Watkins, 1961). Normally absent in arid and semi-arid regions, it becomes a serious disease of summer crops when irrigation is introduced (Avizohar-Hershenson and Palti, 1962).

Irrigation can also affect crop diseases by its effect on soil temperature. For example, optimum temperatures for verticillium wilt of cotton (*Verticillium albo-atrum*) are 20–25°C; no damage occurs to the plant at temperatures above 33°C (Garber and Halisky, 1958). This can explain why irrigation, by reducing soil temperatures, promotes the development of root diseases such as verticillium wilt.

In areas around the Mediterranean, irrigated crops may be planted in early spring; at this time aphids migrate in large numbers from the ageing winter crops and natural vegetation, to the young irrigated crops. Epidemics of cucumber mosaic, maize dwarf mosaic, potato Y and water melon mosaic viruses may occur on the irrigated crops (Thresh, 1982).

Irrigation may increase the incidence of virus diseases indirectly, through its effect on the vector responsible for spreading the disease.

The beet leafhopper (*Circulifer tenellus*) is the only known vector of curly-top disease affecting a number of important crops such as sugar beet, beans, melons,

tomatoes, and others. In regions with cold winters, this vector's successful hibernation, which is essential for a rapid build-up of the population subsequently, is prevented by the low temperatures (Carter, 1961), but in arid regions with mild winters, the vector hibernates on typical winter annuals. When irrigation is introduced into these areas, ideal conditions are offered for the rapid dissemination of the leafhoppers in the green cultivated areas, from which the virus disease is spread to a number of crops (Lawson et al., 1951).

When desert land is first developed for irrigation, a period of relative freedom from plant diseases is usually experienced. However, certain diseases, when once introduced, spread rapidly in these newly irrigated areas, especially if no proper crop rotation is practiced. In the Columbia basin, in north-western N. America, *Fusarium* root rot of beans increased from a trace in the first year of irrigation, to serious damage in the third year, when beans were grown continuously (Menzies, 1954). Many pathogens are introduced with infected seeds, into regions in which the disease that they produce was previously non-existent.

Effect of method of irrigation on plant diseases

Natural precipitation generally favours the incidence of foliar diseases due to fungi and bacteria; it is therefore reasonable to assume that overhead irrigation will have similar effects. Certain authors state that, under semi-arid conditions, the use of a method of surface irrigation instead of sprinkling may contribute more to disease control than does any chemical treatment (Snyder et al., 1965). However, experience has shown that the danger from sprinkler irrigation has been overemphasized, at least for field crops. There are several important differences between natural precipitation and overhead irrigation that are of relevance to the incidence and spread of plant diseases. For many pathogens, infection depends on the length of time that the plants remain wet after inoculation. Precipitation occurs over relatively large areas, usually after a period of cloudy weather, lowered temperatures, and increased air humidity – which conditions may continue for some time after the rain.

Overhead irrigation applies 'rain' suddenly, under conditions of high temperature and light intensity and low air humidity. The irrigated area is an 'oasis', surrounded by hot, dry air. Shortly after irrigation ceases, the foliage of the irrigated crop becomes completely dry. For most plant diseases, free water must be present on the leaf surfaces for periods of not less than 6–12 h, to permit infection to take place. This applies to many of the most important disease agents (Gottlieb, 1950). Secondary sporulation, which leads to the main damage to the crop, requires a considerably longer time (Menzies, 1967). Rainfall, which is effective in causing the spread of these diseases, is usually associated with far lower temperatures than overhead irrigation. The optimum temperatures for spore production, germination and infection, are usually far lower than those prevailing when irrigation is usually necessary (ibid.). Therefore, whereas overhead irrigation may be conducive to infection, the dry hot

weather between irrigations may, in many cases, effectively preclude the survival and spread of the inoculum.

Whilst one should not overemphasize the dangers inherent in overhead irrigation, neither should they be overlooked. Sprinkling differs from other irrigation methods in wetting the foliage of the crop, washing off fungicide deposits, and dispersing inoculum of many fungi. It therefore creates conditions under which the host is more prone to disease, while also favouring the dissemination of the agents of disease and reducing the effectiveness of fungicides at a crucial time.

Although overhead irrigation periods may be of shorter duration than rain, they may extend by a few hours the period of wetness resulting from dew, which also favours the spread of certain diseases. The dew period in arid zones is also greatly extended during irrigation periods (Schein, 1968).

Sprinkler irrigation also affects leaf temperature. In a study in Israel, it was found that when air temperatures were 24 and 29°C in the morning and at noon, respectively, the leaf temperature of unirrigated potatoes was 30 and 36°C, whilst that of the irrigated leaves was only 22°C. When irrigation was stopped, leaf temperatures began to rise, but remained below that of unirrigated plants for the whole day. This may be of considerable significance in dry climates, as the leaf temperatures are frequently critical for infection (Rotem and Palti, 1968).

Though it is less dangerous than rainfall, there is no doubt that overhead irrigation can favour the spread of certain diseases, and is therefore more dangerous in this respect than surface irrigation, as is shown by the following examples:

Bacterial leaf diseases of field beans were found to be far more severe with sprinkling than with furrow irrigation (Menzies, 1954). In the arid Negev, *Phytophthora* blight on potatoes was found to develop profusely under overhead irrigation, whilst it did not occur with furrow irrigation (Rotem et al., 1968). *Cercospora* leaf-spot (*C. personata*) on peanuts also reacted in the same way (Palti and Stettiner, 1959).

For most forage crops, it was found that leaf diseases were more severe under a high moisture régime with sprinkler irrigation than otherwise. The diseases which showed the greatest increase in severity under high-level irrigation were *Pseudopeziza* leaf-spot on intermediate white clover, *Curvularia* leaf-spot on ladino clover, and *Pseudopeziza* leaf-spot on alfalfa (Curl and Weaver, 1958).

In view of the many advantages of sprinkler irrigation (see p. 596), techniques must be adopted to minimize the undesirable effects on disease propagation. This can be done by:

- (a) Avoiding excessive and unbalanced fertilizer applications which are conducive to luxuriant vegetative growth and increased succulence.
- (b) Applying large amounts of water at relatively long intervals of time rather than small amounts frequently.
- (c) Choosing the time of day when sprinkling is least likely to enable the pathogen to complete the infection process; the best solution is to irrigate at night, when plants

are in any case wet with dew. Automatic equipment makes it possible to turn the sprinklers on or off, according to a predetermined schedule. When night-time irrigation is not possible, irrigation should start before dew on the foliage has dried off, and should cease in time for the foliage to dry before the next night's dewfall (Palti, 1981).

(d) Allowing each irrigated strip to dry before irrigating the adjacent strip (Rotem and Palti, 1968).

It has been shown experimentally that numerous light sprinkler irrigations, applied at short intervals of time, aggravate the damage caused to groundnuts by pod rots (*Pythium* spp.) as compared with an equal total amount of water applied in heavier irrigations at longer intervals. Allowing the top soil to dry for a few days before resuming irrigation, after the onset of the main blossoming period, was fairly effective in reducing the damage caused by pod rots (Frank, 1967).

One technique to reduce incidence of seedling diseases at the time of germination and emergence, when most crop plants are especially susceptible to attack, is to irrigate before sowing, wetting the soil to field capacity to the full depth of the root zone, allow the top soil to dry, and then sow into the moist soil underneath. The seedlings emerge through dry soil, preventing 'damp-off'. The same method helps to control weeds (cf. p. 798) and has additional advantages in water use efficiency.

Flooding and furrow irrigation can spread inoculum of bacteria, nematodes, and soil-borne pathogens from plants to plants in the direction of the flow of water. At the lowest points of the fields, the inoculum may accumulate and cause heavy infection (Palti, 1981).

On the other hand, flooding to control diseases is an age-old, key practice for the control of soil-borne diseases, developed in China for crops grown in rotation with rice. It is still used in regions with intensive vegetable production in the lower Yangtze and South China (Kelman and Cook, 1977).

The benefits of trickle irrigation for plant protection have been reviewed by Palti and Shoham (1979): the avoidance of periodic water stress common with other irrigation methods, is effective in guarding crops from predisposition to diseases such as *Alternaria* blights and powdery mildews. Inoculum is no longer splashed about, as with overhead irrigation, which practically eliminates certain diseases, such as *Glomerella cingulata*. By reducing soil temperature, trickle irrigation reduced infestation by *Sclerotium rolfsii*, following increased activity by micro-organisms antagonistic to the pathogen.

However, the incidence of pathogens that thrive at lower temperatures and constant humidity, such as *Rosellinia necatrix*, is increased by trickle irrigation.

Plant nutrition and disease

Plant nutrition affects growth and development, morphology, anatomy, and espe-

cially composition of plants, and can thereby influence their resistance to diseases. Thicker epidermal cells, the formation of physical barriers through lignification or silification, and a higher production of repelling or toxic substances, are examples of factors increasing the plant's resistance to diseases that can be influenced by nutrient supply (Marschner, 1986).

Under optimal conditions of nutrition, plants produce sufficient photosynthates to meet all requirements for vegetative and reproductive growth. Under stress induced by nutritional deficiencies, the vigour of a plant is reduced below a certain level, and the plant becomes susceptible to invasion by weak parasites, and even by saprophytes.

In some cases, a high level of soil fertility, with the attendant abundant nutrient supply, may be conducive to certain diseases. Stalk rots and root rots of maize are an example of disease that generally increases with soil fertility (Hooker, 1966).

Most of the available evidence indicates that it is not the high level of fertility per se that is the cause of increased disease incidence, but the lack of balance between nutrients, in particular between N and K, which seems to play the major role in the development of stalk rot and root rot.

As a rule, disease incidence of highly susceptible cultivars will only be marginally influenced by mineral nutrients; similarly, nutritional effects on resistant cultivars will also be minimal. It are the moderately susceptible or partially resistant cultivars which respond most significantly to manipulation of nutrient supply through fertilizer application (Grossman, 1970).

Nitrogen effects on crop disease

Nitrogen increases plant vigour and growth and thereby has a marked influence on susceptibility to disease. High N rates favour the formation of thin-walled cells, large intercellular spaces and open stomata, all features conducive to pathogen infection, especially bacterial pathogens (Grossman, 1970). It is also well established that the phenolic content of plants and their fungistatic effects decrease with high levels of N supply (Kiraly, 1964).

As a general rule, vigorously growing crops are more susceptible to obligate pathogens, such as rusts and powdery mildews of wheat and barley, and viruses such as tobacco mosaic virus, while low-vigour crops are most prone to attack by the majority of facultative pathogens such as *Alternaria* blights on many crops and most bacterial diseases, such as *Xanthomonas* (Palti, 1981). The reason for these differences in response is that obligate pathogens require a supply of assimilates from living cells, while facultative pathogens (which are semi-saprophytes) prefer senescing tissues, and may release toxins to kill host plant cells (Marschner, 1986).

The nutritional requirements of viruses are confined to amino acids and nucleotides. As a rule, nutritional factors that favour host plant growth also favour viral multiplication. However, visible symptoms of viral disease may either disappear

when N supply is high (e.g., sugar-beet yellow) or be enhanced (e.g., tobacco mosaic virus) without change in the level of infection (Marschner, 1986).

Nitrate or ammonium? Plant-pathogen interactions frequently depend more on the specific form of nitrogen applied (NO_3^- or NH_4^+) than on the amounts of N available (Henis, 1976). Wilts and root rots caused by *Fusarium* spp. and *Rhizoctonia solani* are favoured by NH_4^+ , while root rots due to *Pythium* spp. and wilts due to *Verticillium* spp. are favoured by NO_3^- (Huber and Watson 1974).

Walker (1969) states that increasing the NH_4^+ taken up by the plant, plus the increased acidification in the rhizosphere associated with the use of sulphate of ammonia, reduces the infection of take-all root rot. Conversely, NH_4^+ favours *Pseudocercospora* eye-spot (Huber and Watson, 1974).

Some N compounds are directly or indirectly toxic to certain fungi. For example, Lachover and Avizohar-Hershenson (1960) have shown that aqueous ammonia reduces the incidence of *Sclerotium rolfsii*, a disease that causes considerable damage to many irrigated crops in the Mediterranean region. Ammonia has a similar effect on *Phymatotrichum omnivorum* on cotton. Calcium cyanamide has a toxic effect on several soil-borne pathogens, including *Sclerotium rolfsii*. Urea, applied as a spray, is toxic to various foliar pathogens (Fuchs and Grossman, 1972). Ammonia is highly toxic to certain *Fusarium* spp. and nitrite (formed during the oxidation of NH_4^+ to nitrate) is toxic to *Pythium* and *Phytophthora* (Henis, 1976).

Palti (1981) points out that the dilemma facing the farmer in his choice of N carrier, is that almost all major crops are subject to some diseases favoured by nitrate as well as to other diseases favoured by ammonium. His decision will therefore have to be based on which disease is most likely to attack his crop, or which is likely to cause the greatest damage.

Phosphorus

Generally, favourable effects of fertilizer P in reducing damage caused by diseases appear to be connected with correcting nutrient balance in crops grown on P-deficient soils, or in advancing maturity, and thereby helping the crop to escape from obligatory parasites that prefer younger tissues (e.g., downy mildews) (Palti, 1981).

Potassium

Potassium has been shown to raise the disease resistance of many crops. How potassium is involved in influencing the severity of plant diseases is still not very well understood; it is assumed that it may partly relate to the promotion by K of the development of thicker outer walls in epidermal cells (Mengel and Kirkby, 1982). Disturbed plant metabolism in K-deficient plants is also conducive to increased susceptibility to diseases because the synthesis of proteins, starch and cellulose is impaired and low-molecular-weight organic compounds accumulate (Marschner, 1986).

Soft rot bacterial diseases (e.g., *Erwinia* spp. and *Xanthomonas* spp.) usually enter the plant tissue through wounds. In K-deficient plants, the rates of wound cork formation are low, thereby increasing the severity of infection (Leuchs, 1959). Virus diseases are usually not affected by levels of available K (Palti, 1981).

In contrast to nitrogen, potassium increases resistance to both obligate and facultative pathogens. Generally, no resistance increases result from increasing the K supply beyond the optimal level for growth, and in many cases the effect of K is confined to the deficiency range (Marschner, 1986).

The most important contribution of potassium fertilizers in irrigation agriculture is to offset to some degree the negative effects of heavy applications of nitrogen that are required for high yields but increase the plant's susceptibility for disease.

Calcium

Many fungal and bacterial pathogens invade plant tissue by producing pectolytic enzymes; it is well documented that calcium drastically inhibits the activity of this enzyme and thus enhances plant resistance to the aforementioned pathogens. Various fungal pathogens, such as *Fusarium*, preferentially invade the xylem and dissolve the cell walls of conduction vessels, causing plugging of the vessels and subsequent wilting symptoms. The severity of the attack is closely related to the level of Ca in the xylem sap (Marschner, 1986).

Pre-harvest pod rot of groundnuts, caused by *Phythium myriotilum* and *Rhizoctonia solani* is closely related to the Ca content of the pod tissue and can be kept at a low level by applying gypsum (Hallock and Garren, 1968).

Other factors influencing disease

Soil compaction

Soil compaction, such as that resulting in plough soles, favours attack by certain diseases. Barley stunt, due to *Rhizoctonia*, root rot of peas, as well as of beans, due to *Fusarium solani*, soybean nematodes (*Hoplolaimus columbus*) are examples of diseases that can be prevented or alleviated by loosening up the soil in deeper layers and facilitating deeper penetration of roots (Palti, 1981).

The dreaded cotton root-rot disease *Phymatotrichum omnivorum* is most severe in poorly aerated, heavy clay soils, where the production of sclerotia is favoured by high levels of CO₂ (Lyda, 1978).

Crop residues

Most leaf-, stem-, head-, and fruit-infecting organisms are entirely, or almost entirely, dependent on host residues where they survive between crops, to produce inoculum for their next attack (Boosalis and Doupnik, 1976). When the residues are buried in moist soil, these pathogens usually do not survive for more than a few months. They may persist for longer in very dry or cold soils, where competitive

organisms are less active. Therefore, leaving crop residues on the soil surface greatly enhances the possibility of survival of these pathogens (Cook et al., 1978).

Many root-infecting organisms also depend for their food and survival on crop residues; however, in contrast to the pathogens of the aerial parts of the plant, burial of the crop residues actually improves their inoculum potential (ibid.).

Some pathogens, such as *Sclerotium rolfsii*, are also effective as saprophytes and colonize residues of their host crops or of non-hosts, and increase thereby their inoculum potential. As these are active only on or above the soil surface, infection can be reduced or controlled by complete burial of all debris (Cook et al., 1978).

Cercospora herpotrichoides is the causal agent of foot-rot disease of wheat, which is entirely dependent on host tissue for survival and reproduction, and whose severity of attack is directly related to the amount of infected host tissue on the soil surface. Yet, in the course of an eight-year trial, disease incidence in stubble-mulched plots was found to be the same as in clean-tilled plots (Cook and Waldher, 1977). Other authors have observed opposite effects, with foliar diseases, in which the severity of attack was increased with conservation tillage. Cook et al. (1978) conclude that the newer tillage methods, which leave appreciable amounts of residue on the soil surface, will increase the importance of breeding disease-resistant cultivars, as the most practical way to overcome these problems.

Crop residues influence plant diseases in a number of ways, as the decomposition process involves various microbiological interactions and the production of fungitoxic decomposition products.

A major benefit of certain crops in the rotation is the root disease control resulting from incorporation of the crop residues in the soil. Organic amendments can reduce the populations of many root-infecting fungi by inducing germination of propagules followed by lysis and death (Cook et al., 1978).

Control may also be the result of competition for nutrients. When residues with a high C : N ratio are incorporated into the soil, immobilization of the nitrogen by saprophytes may cause N-starvation of certain root rots, such as that caused to beans by *Fusarium solani* f.sp. *phaseoli* (Cook et al., 1978).

Major pathogens of plants

Walker (1969) proposed the following categories of plant pathogens:

Obligate parasites depend on living plants at all stages of development of the pathogen. Only a few taxonomic groups of fungi are obligate parasites. These include the *uredinales* (rusts), *erysipales* (powdery mildews), higher *peronosporales* (downy mildews), and some others. The viruses are obligate.

Facultative parasites comprise micro-organisms that are mainly saprophytic but are capable of attacking hosts weakened by stress conditions. Many soil-borne

micro-organisms, such as *Pythium* spp., *Verticillium* spp., and *Rhizoctonia* spp. are typical facultative parasites.

Facultative saprophytes are normally parasitic micro-organisms that have a limited ability to feed on dead organic matter. *Ustilaginales* belong to this group.

Obligate saprophytes feed exclusively on decaying organic matter. Moulds are typical obligate saprophytes, but can cause considerable post-harvest damage to agricultural produce.

The principal agents of infectious diseases are: fungi, bacteria, viruses, and mycoplasma.

Fungal diseases

General features

Fungi are now considered as distinct from the Plant Kingdom, because they lack photosynthesis, and form a Kingdom of their own (Ainsworth et al., 1973).

Fungi are eucaritic thallophytes that contain no chlorophyll, and therefore absorb nutrients from organic material, previously photosynthesized by higher plants.

Stages of infection

Primary inoculum. After a host plant dies, the pathogen must survive until the following season. Wintering or summering takes place in the soil, on plant residues, or on alternative hosts; survival during these or other unfavourable periods is assured by resting spores: oospores, ascospores, teliospores, etc., or by vegetative organs, mainly *sclerotia* (a mass of hardened and compressed mycelium) and chlamydospores (thick-walled spores).

Transmission to the host plants is through seeds, planting material, wind, rain, irrigation water, and various vectors: insects, animals, and man. On infected plants, transmission occurs from leaf to leaf, and from plant to plant.

Pathogen development in the host plant. Inoculation occurs when the inoculum reaches sites on the host plant from which infection can occur (infection courts).

Time and intensity of infection are determined by the presence of moisture on the plant's surface or in the air, temperature (optimum generally between 15 and 25°C), amount of inoculum present, and susceptibility of the host plant. The presence of large amounts of inoculum can compensate pathogens for the environmental constraints encountered in dry climates (Rotem, 1978). When humidity and temperature are favourable, and the density of inoculum has reached a high level, explosive outbreaks of a disease may occur (Palti, 1981).

After a period of incubation, the pathogen penetrates into the plant tissues. Some fungi are able to overcome the natural physical barriers against infection – the cuticle and the epidermis – others can only penetrate through stomata or fresh wounds.

Actual infection starts when the pathogen and the host plant begin to interact. In *localized infection* the pathogen remains close to the original site of penetration; the spores produced transmit the diseases to other parts of the plant in a secondary process of infection. In *systemic infection* the pathogen spreads through the plant tissues. Some pathogens are capable of causing both types of infection.

Pathogens spread in the host plant by excreting toxins and enzymes that destroy plant tissues (necrosis).

Reproduction. In the vegetative stage, the body of a fungus consists of branching thread-like structures: the hyphae, which together form an interlacing web called mycelium. Mycelium may form outside or inside the host plant.

Reproduction is either asexual, by means of zoosporangia, conidia, and ure-dospores, or sexual: oospores, ascospores, and basidiospores. Dispersal of fungi occurs by means of spores; spores are tiny bodies, the size of dust particles, that are produced in enormous numbers.

Economic importance

All economic plants are attacked by one or more of the 8000 species of pathogenic fungi which cause the majority of plant diseases, many of them extremely destructive. The direct cost of crop diseases cannot be estimated correctly. The overall loss in developing countries is certainly far greater than is the case for developed countries; in addition to a lack of effective disease control, the combination of warm climate and irrigation in the dry regions in which many developing countries are found, provides excellent conditions for the spread and intensity of crop diseases.

Disease control

Disease control methods aim at preventing the build-up of inoculum, evading infection, and increasing the resistance of crops to infection – or improving its ability to recover from infection.

Fungal diseases are usually controlled by some combination of cultural practices, chemical control, plant resistance, and biological control.

Use of chemicals

Since the advent of the Bordeaux mixture in the middle of the 19th century, many chemicals have been developed for the control of plant diseases. Since 1934, more than 300 general and specific fungicides have been developed, with at least twice as many formulations (Kommendahl and Windels, 1979).

Foliar fungicides. Most of these are effective only as external prophylactics; they do not control the disease when once it is established, and they have no effect on pathogens within the vascular system of the plant.

The great difficulty in designing new plant protectants is the need for selective toxicity to the pathogens, without excessive phytotoxic effects. In this respect the organic fungicides, first developed shortly before the Second World War, are far superior to the inorganic copper, sulphur, mercury, and zinc compounds, which were available to farmers before the advent of the organics. The most widely used of these newer compounds are the alkylene bisdithiocarbamates, such as nabam, zineb and maneb. These are essentially inert materials – until they undergo decomposition at a controlled rate, which releases a toxicant that destroys fungous spores with which it comes in contact. Proper formulation increases the effectiveness of the fungicides (McNew, 1966).

Captan and folpet are trichloromethyl thiocarboximides, and are effective against leaf spots, blights, and rots on various vegetables, ornamentals, and fruit (Kommendahl and Windels, 1979).

Use of chemotherapeutants. Systemic chemotherapeutants, capable of attacking pathogens within the plant, appear a priori to be the most efficient approach to plant protection. However, host and pathogen tend to have very similar biochemical systems; chemicals that are effective in suppressing the pathogen were generally too phytotoxic or too expensive.

A breakthrough came with the discovery of the systemic fungicides benzimidazoles, oxathiins, and pyrimidines. Of the benzimidazoles, benomyl is very effective and has a wide spectrum of application. Among the pyrimidines, dimethylthiramol is specifically systemic in cucurbits, in which it controls powdery mildews; triarimol is a systemic protectant that controls powdery mildew, rusts, *Cercospora*, and others.

Antibiotics have generally not been effective as foliar fungicides (Kommendahl and Windels, 1979).

Chemicals used for influencing crop physiology. Chlormequat (C.C.C.) used for prevention of lodging in wheat, has been found to reduce incidence of eye-spot (*Pseudocercospora herpotrichioides*), and to mitigate cotton wilt (*Verticillium dahliae*). Other materials, such as hormonal sprays have been found to contribute to crop sanitation or reduce hail and frost damage, thereby minimizing infection by pathogens (Palti, 1981).

Seed treatments. In damp weather, when the fungal flora in the atmosphere is abundant, a great number of pathogens can colonize the seed during its formation. Some micro-organisms are present under the seed coat; these have already infected the reproductive organs at the flowering stage. Other micro-organisms can colonize the seed coat during storage. The final source of inoculum for the seed and emerging seedling is the soil (Lynch, 1983).

Chemicals used in the past for treating seed have been compounds of copper or mercury, and organic compounds involving sulphur. Organic mercury compounds

were very effective, but were replaced by a dithiocarbamate – thiram. Later came the quinones, such as phygon, used to treat seeds of cotton, crucifers, and legumes, and captan – a trichloromethylthiocarbooximide – used extensively on maize and many other crops.

From the chemicals for external application, attention subsequently moved to systemic chemicals, mainly the benzimidazoles (benomyl) and the oxathiins. Applied as seed dressings, they are translocated to protect roots and foliage. Benomyl is effective for the control of *Ascochyta pisi*, take-all in wheat (*Ophiobolus graminis*) and for a variety of foliage diseases. Thiabendazole controls dwarf bunt of wheat (*Tilletia caries*).

The oxathiins, carboxin, and oxycarboxin, are specifically effective against basidiomycetes. Mixing carboxin with certain other chemicals, widens the spectrum of diseases that can be controlled: e.g. mixed with copper oxyquinolate it acts synergistically to control *Septoria nodorum*, *Helminthosporium gramineum*, and *Fusarium nivale* on wheat and grasses. Carboxin with chloroneb are taken up by the roots of sugar beets, and protect the crop from infection by *Sclerotium rolfsii* (Kommendahl and Windels, 1979).

Experience has shown that as one moves from the more non-specific fungicides, such as phenyl mercuries, to the more specific fungicides, such as carboxin, the danger of giving rise to resistant mutants of the disease agents increases (Ellingboe, 1980).

Seed inoculation with bacteria and fungal spores has also been investigated and offers considerable promise for biological control against seed-borne and soil-borne pathogens (Curl and Truelove, 1986). Among the bacteria showing high potential are: *Agrobacterium radiobacter*, *Bacillus subtilis*, and *Pseudomonas fluorescens*; among the fungal seed protectants are species of *Penicillium*, *Trichoderma*, *Gliocladium*, and *Chaetomium* (Kommendahl and Windels, 1981).

Merriman et al. (1974) report that seed inoculation with *Bacillus subtilis* and *Streptomyces griseus* has induced increased marketable yields of wheat, barley, oats, and carrots. Both these organisms are antagonistic to *Rhizoctonia solani*, but, surprisingly, did not influence disease incidence. The observed benefits were therefore, in this case, due to some other factor(s), possibly the synthesis of growth factors by the inoculant micro-organisms.

Phytoalexins. When an avirulent race infects plant tissue, the plant may respond by producing substances known as phytoalexins, which may prevent subsequent infection by virulent pathogens. The phytoalexins are produced as the result of a hypersensitive reaction of the plant to pathogens (Lynch, 1983).

*Control of soil-borne diseases.**Chemical treatments*

A large volume of chemicals would necessarily be involved when applied to the soil. Fungicidal activity and effectiveness of these chemicals depend on the amounts adsorbed by soil colloids, degraded by biological or non-biological factors, volatilization, leaching, and plant uptake. The chemicals should be effective against pathogens, but should not harm saprophytes. Because of these limitations, chemical treatment of soils for the control of the most soil-borne diseases is too expensive for routine use in the field. For these reasons, major efforts are directed to preventing a build-up of inoculum potential.

Seed treatment

Chemicals used in seed treatment have already been mentioned, these affect mainly pathogens in the rhizosphere. Because the seed placed in moist soil and the emerging seedling are most vulnerable to soil pathogens, a coating of relatively small quantities of seed dressing provides an immediate competitive advantage for antagonists to colonize the spermosphere and the young seedling root, at least for a short time, permitting the seedling to escape the pre-emergence and early post-emergence phases of damping-off caused by unspecialized pathogens such as *Rhizoctonia solani* and *Pythium* spp. (Curl and Truelove, 1986).

The major drawback is that after sowing, microbial degradation of the seed dressing can rapidly degrade it; also, very few of the chemicals available are completely satisfactory against the full range of pathogens the seed and the emerging seedling may encounter (Lynch, 1983).

Biocontrol agents are most effective when the seed is sown under suboptimal conditions for germination and plant growth, for example cotton and maize sown early in spring, in relatively cold soil (Lynch, 1978).

Cropping sequences

By maintaining a sufficiently long interval between susceptible crops, during which non-susceptible crops are grown, the population of soil pathogens is contained within reasonable levels.

Decoy crops are non-host crops, which are included in the crop sequence, in order to activate the dormant propagules of soil-borne fungi (as well as seeds of parasitic plants, and larvae of nematodes) and thereby waste their infection potential.

Crop rotations that include non-host plants, can be useful for reducing damage by highly specialized pathogens, that develop and reproduce only on the roots of specific

host crops; others, which can lead a saprophytic existence, may survive for long periods between susceptible crops.

Relatively short rotations may be very effective in limiting damage by pathogens, such as *Altenaria*, *Cercospora*, and *Colletotrichum*, whose propagules may accumulate in crop residues or in the surface layers of the soil.

Antibiosis. Some sequences of non-susceptible crops have a drastic effect on soil pathogens, such as cannot be attributed solely to the absence of a suitable host. These effects may be due to root secretions of organic acids, amino-acids, or carbohydrates, that influence the balance among micro-organisms in the rhizosphere; this influence may be exerted by direct toxic effects on the pathogen, by stimulating antibiosis, or by increasing the numbers of antagonistic micro-organisms (McNew, 1966). The soil abounds in powerful antagonists that compete with parasites or poison soil-borne plant pathogens. They are selective for the pathogens they attack, and are also selective for the kinds of organic materials upon which they thrive (Snyder, 1960). Legumes can reduce take-all disease in wheat (*Ophiobolus graminis*) by fixing soil nitrogen and thereby starving the fungus (Garrett, 1965). The crop residues of sweet clover, grown in rotation with cotton, reduce infection by texas root rot of cotton (*Phymatotrichum omnivorum*) presumably by stimulating the activities of bacteria that are antagonistic to the pathogen (Lyle et al., 1948).

Another method of achieving the same effect is the ploughing under of a green-manure crop. Where *Phymatotrichum* root rot of cotton is serious, the turning under of a pea crop for green manure makes it possible to harvest a crop of cotton. This is a standard practice for combating root rot of cotton in Arizona (Snyder, 1960).

The effects of crop residues vary according to the kind of residues and the micro-organisms involved. In general, oat and lucerne stems reduced the severity of root diseases of wheat, whilst wheat and barley residues increased their severity (Curl, 1963).

Oat residues reduced stem-rot severity of groundnut seedlings due to *Sclerotium rolfsii*, as compared with groundnut or clover residues. In the oat-residue soil, the activity of *Trichoderma*, and its potential as a biological control agent of *S. rolfsii*, were enhanced (Mixon and Curl, 1968).

Huber et al. (1965) found that crop residues which increased the rate of nitrification reduced the severity of *Fusarium* and *Rhizoctonia* infection, whilst residues that inhibited nitrification increased disease severity.

Burning crop residues

Pathogens concentrated very near to the soil surface are vulnerable to control by the heat or smoke generated by burning crop residues. The effective depth of control depends on the amount of residues that are burned. The heat treatment by burning was as effective as heating by solarization (Cook, 1990).

Biological control

Because of the intensity of antibiosis in the soil and its sometimes drastic effects on soil pathogens, biological control of soil-borne diseases appears, a priori, to have a great potential for success. Curl and Truelove (1986) describe the frustrations encountered in this approach: "Plant pathologists, more than any other group, have experienced, with considerable anguish, the true meaning of antagonism when attempts have been made to establish potential biological control agents in a natural field soil. Such attempts have often failed due to the greater competitive or other antagonistic action of endemic components of the microflora against the introduced organism".

For example, *Trichoderma* spp., are very common antibiotic synthesizing micro-organisms; they have all the attributes required to be strong biological control agents against pathogens, and are inhibited by very few other fungi. And yet, it is difficult to establish *Trichoderma* in natural soil as a supplementary biological control agent, probably because of interference by bacteria and streptomycetes. The antibiotics produced are also generally chemically and biologically unstable (Baker and Cook, 1982).

The use of natural enemies is still being explored. The use of biological seed inoculants has been mentioned above. Competition between bacteria and *Fusarium oxysporum* resulted indirectly in the suppression of the fungus as the result of biologically induced nitrogen deficiency, as evidenced by the fact that the addition of N fertilizer cancelled the competitive effect of the bacteria (Marshall and Alexander, 1960).

Curl and Truelove (1986), after reviewing the literature on the subject, conclude that "while antibiotic production by many bacteria, actinomycetes and fungi, and the resulting antibiosis, have been demonstrated numerous times in laboratory cultures, the status of antibiosis in a natural environment remains controversial".

Suppressive or resistant soils

Certain soils tend to resist the pathogenic activity of fungi; crops grown on such soils are either not attacked by certain diseases, or the disease declines after a time. For example, take-all declines after it has peaked in the third or fourth year of continuous wheat growing on such soils. This phenomenon, though not completely understood, is thought to be due to the production of microbial antagonists (Lynch, 1983).

Soil sterilization

Because of the expense involved, soil sterilization is economically justified only for high-value crops; when these are grown in monoculture or on greenhouse soils, soil sterilization is the only possible method to ensure sustained high-level productivity. The procedure generally eliminates many root diseases, but the major targets are generally nematodes and weed seeds.

The fumigants used for this purpose are volatile, non-selective, and destroy most pathogens (as well as nematodes), and delay recolonization by beneficial saprophytes (Kommendahl and Windels, 1979). Phytotoxic soil disinfectants include: ethylenedibromide, methylbromide, methyl isothiocyanate, 1,3-dichloropropene; among the non-phytotoxic compounds are: aldicarb, carbofuran, oxamyl, phenamiphos (Kranz et al., 1977).

Solar heating (solarization)

The application of solar radiation to the soil before sowing as a method of for the control of soil-borne fungi, nematodes, and parasitic plants in arid and semi-arid irrigated zones was developed by Katan and co-workers in the early 1970's and has proven to be effective in certain cases. The method consists of irrigating and subsequently covering the soil with polyethylene plastic.

The depth to which the solar heating is effective depends on the intensity of radiation, the duration of the treatment, and the pathogen. At monthly maxima of 49–52°C soil temperature at 5 cm, and of 42°C at 15 cm depth, *Verticillium dahliae* was eliminated to a depth of 25 cm, and *Fusarium oxysporum* f. sp. *lycopersicum* significantly reduced (Katan, 1980).

Disease prevention methods

A basic difficulty in designing crop production methods which will minimize the dangers of infection by disease is that plant pathogens generally have environmental requirements very similar to those of their hosts, so that conditions conducive to high production by the crop are also, a priori, favourable to the pathogen.

However, many crop diseases can be avoided or kept in check by the use of certain preventive measures and suitable agronomic practices.

Predicting disease outbreaks

Effective short-term predictions of disease outbreaks can contribute to a reduction in the number of preventive treatments required. These predictions are based on (a) field monitoring, whereby the present disease situation is extrapolated to the future; (b) weather forecasts (especially suitable for downy mildews); and (c) various value point systems, where a number of circumstances are each given a certain numerical value, the sum of which constitutes a risk assessment (Zadoks, 1989).

An important measure to reduce the probability of epidemical spread of diseases is to avoid what Zadoks (1989) calls a 'green bridge' which spans the gap from one crop season to the other. Irrigation, as well as staggered planting, provide such a bridge.

Burning crop residues

Burning crop residues reduces some diseases (cf. p. 898) in particular those of peren-

nial crops; it does not eliminate or even reduce other residue-borne diseases, such as *Verticillium albo-atrum* in potatoes, and various wheat foot-rot fungi (Cook et al., 1978). These authors conclude that the amount of pathogen inoculum destroyed by burning crop residues is not sufficient to offset the disadvantages of lost organic matter.

Eradication of alternate hosts

Eradication of species of barberry for the control of black stem-rust of wheat (*Puccinia graminis*) has already been mentioned (p. 791). It is estimated that, in the United States alone, the campaign for eradicating barberry reduced annual losses due to the disease to one-fifth of their original level (McNew, 1966). For the prevention of virus disease, the choice of sites in which the disease vector is absent, and the choice of sowing dates at which the vector is not yet active, are very effective preventive measures. Moreover, chemical control of the vectors that persistently transmit viruses became practicable after the introduction of systemic insecticides. Whilst the control affected by systemic insecticides is not absolute, as the vector insect may transmit the disease before the insecticide has taken effect, the losses from virus diseases can be considerably reduced by their use.

Clean seed and seed treatment

Disease-free seed, combined with crop rotation, has helped to prevent the spread of several seed-borne diseases, especially in vegetable crops, such as black rot and black leg of crucifers, anthracnose and bacterial blights of legumes. Certified potato tubers, imported from areas in which virus vectors are not active, are the major means to prevent the introduction of viral diseases such as mosaic and leafroll (Hanson et al., 1979b).

The importance of seed treatment in preventing the spread of diseases cannot be overstressed (cf. p. 894, 895).

Planting patterns

The aim is to improve air movement and promote the rapid drying of the foliage by such means as avoiding dense plant populations, e.g., check-planting – which has helped to retard the spread of *Cercospora beticola* in sugar beets (McNew, 1966).

Nutrition

The quantity and balance of nutrients supplied to the crop have a considerable bearing on its susceptibility to disease.

Crop nutrition can be manipulated in a number of ways to protect crops from pathogens (Palti, 1981):

- by avoiding nutrient strain, the plants are better able to resist attack;
- by creating a nutrient supply more favourable to the crop than to a specific pathogen;

- by stimulating microbiota competing with, or antagonistic to soil-borne pathogens.

Breeding for disease resistance

The use of disease-resistant cultivars is without doubt the most effective and economical method of disease prevention, especially for those diseases for which no economical chemical control method has yet been developed. In many cases, the continued cultivation of a crop in a certain area became possible only after resistant cultivars had been developed.

Plant traits that isolate the pathogen at the point of entry, that inhibit pathogen growth, that detoxify the toxic substances produced by the pathogen, or enable the plant to grow under environmental conditions unfavourable to the pathogen, can contribute to resistance.

Nature of disease resistance

Wild species of plants and their parasites have apparently evolved into equilibrium, as each has accumulated a large number of genes – for resistance by the former, and for aggression by the latter. As a result, wild species in their natural habitats sustain some level of disease which they can tolerate.

New genes, in either host or parasite, did not disrupt this equilibrium because of the presence of many other genes that had co-evolved over time.

Genes for resistance to disease have been found in many wild species related to our cultivated crops, and effective plant breeding methods have been developed for transferring these genes to cultivated varieties within a relatively short time. The basic difference between breeding for disease resistance and breeding for other physiological or morphological characters of the crop plant is that, in the latter case, the plant breeder is concerned with a single biological entity, whilst in the former case he must work within two biological systems and their interactions, namely the host plant and the pathogen. Many of the pathogens have a considerable number of physiological races, each capable of attacking one or more varieties of the host plant. The black stem-rust of wheat, for example, has over 200 recognized parasite races.

Sometimes disease resistance may persist for a long time; for example, resistance of cabbage varieties to *Fusarium* has persisted for over 60 years. More frequently, resistant genotypes that have been bred were found to be susceptible by the time they were released for commercial production.

Breakdown of disease resistance

New virulent races may develop by hybridization, and may build up to epidemic proportions within three to five years, leading to the collapse of resistance of established varieties. On the other hand, the breeding of resistant varieties takes about ten years, even with easy-to-handle crops, whilst their life expectancy does not exceed 5

to 15 years (McNew, 1966). The use of pure, homozygous crop varieties – bred to almost absolute uniformity – is also a major factor facilitating the rapid breakdown of disease resistance, by increasing the potential for adjustment and rapid propagation of new virulent pathogenic races.

The work carried out in recent years at the International Maize and Wheat Improvement Center, located at Chapingo, Mexico, is an illustration of the need for a continuous, dynamic plant breeding programme in order to cope with the ever-changing spectrum of prevalent virulent races of cereal rusts (Stakman et al., 1967).

In the autumn of 1948, four outstanding varieties of wheat that had been bred at Chapingo were first released to farmers. These varieties derived their rust resistance from two sources: the ‘Hope’ type, due to a Yaroslav emmer parent, and the ‘Kenya’ type, probably due to a *Triticum turgidum* parent. As a result of their spectacular success, by 1951 no less than 70% of the total wheat acreage in Mexico was sown with one or another of these four superior wheat varieties. Stem rust was apparently under control. However, in the summer of 1950, race 15B, a hitherto non-virulent race of stem rust in the northern USA, suddenly spread like wildfire in the northern USA and southern Canada, ruining late fields of varieties whose near-immunity to rust for more than a decade had finally broken down. Race 15B was carried into Mexico in the autumn of 1950, and the following year, completely ruined late-sown crops of the varieties with ‘Hope’ type resistance. In the summer of 1953, race 139, another rare race which had hitherto shown only limited and weak parasitism, caused the breakdown of the varieties with ‘Kenya’ type resistance.

In the meantime, new varieties had been bred that combined ‘Hope’ and ‘Kenya’ types of resistance. This was, however, matched by another major shift in the population of stem-rust races, with the suddenly increased virulence in 1953 of the two races 29 and 48.

The continuous breeding programme, based on hybridization between varieties of very diverse parentage, and encompassing some 50 000 varieties and hybrid lines in the breeding nursery, was able to make more resistant varieties available as the changes occurred, thereby averting a catastrophe.

Factors involved in disease resistance

Genetically controlled resistance may be due to physiological, morphological, or anatomical, characteristics of the plant.

Physiological factors. Resistance may be due to the nature of the reaction of the cells of the hostplant to the invasion of the pathogen. Obligatory parasites, such as the wheat rusts, cannot maintain themselves except on living plant tissues. If there is full adaptation of the pathogen to the host, the disease will establish itself and spread rapidly. In the field, the whole spectrum of host–parasite relationships may occur from absolute incompatibility – which confers immunity on the host – to complete compatibility, in which case the parasite will completely invade the plant.

Resistance mechanisms are often chemical in nature, and they may occur naturally, e.g., the chemical compounds are present in the host tissues prior to attack by disease, or they may be induced as a result of contact with the pathogen. Chemical defences are more easily neutralized than are morphological defensive traits (Parlevliet, 1981).

The presence of anthocyanin in the plant tissues frequently confers some degree of disease resistance. Resistance to rust is related to the amount of phenols present in wheat tissues.

In linseed it has been found that varieties which have the same types of protein as the fungus causing linseed rust (*Melampspora lini*), are susceptible to the disease, whereas those in which this type of protein is absent are resistant (Flor, 1956).

Morphological factors. Disease resistance may be due to certain morphological characters, such as hairiness or a waxy covering of the vegetative parts. Certain pathogens penetrate into the plant tissues through the stomata, the size of which, and the length of time during which they are open, have relevance to the susceptibility of the plant to infection. In wheat, for example, it was found that the plants most susceptible to rust were those in which the stomata are wide open during the early morning hours, at a time when the plants are wet with dew and conditions for infection are optimal (Hart, 1949).

The dwarf wheats, in addition to their increased ability to resist lodging, are also less prone to infection by stem rust, because their stems are better protected by the leaf sheaths than are those of the long-strawed varieties.

Some barley varieties have strongly closed glumes which effectively prevent infection by pathogens that penetrate through the open flowers. This trait is non-specific in its resistance mechanism as it excludes loose smut (*Ustilago nuda*) as well as ergot (*Claviceps purpurea*).

Disease avoidance. Many varieties are not attacked by certain diseases because the stage of growth at which the plant is most susceptible to attack does not coincide with the periods during which the pathogen is most virulent. Early maturing varieties of wheat, for example, may thereby escape severe damage from rust epidemics.

New approaches to breeding for disease resistance

The rapid breakdown of resistance in varieties in which attempts have been made to build up specific resistance by adding genetic sources of resistance to the known races of a particular disease, and which are therefore always one step behind a new physiological race of the pathogen, has led plant breeders to search for new approaches to the problem.

Jensen (1988) writes: "The incredible adaptation shown by the stem rust organism has kept plant pathologists and breeders striving to attain a consistent level of control

over this pest. Somewhere there is – must be – a lock to which the organism cannot fashion a key”.

Pathologists and plant breeders have initiated a novel approach: to anticipate the virulence genes that are likely to occur in the field, by artificially creating mutants (using safety precautions against accidental release). This can enable the scientists to search for, and stockpile, new resistance genes of possible future value (McIntosh, 1976).

Multigenic resistance. The basic concept underlying the breeding of cultivars with multigenic resistance is the assumption that it is highly improbable that a new race of pathogen will be able to acquire, by a random breeding process, several genes for virulence, which at one and the same time would enable it to overcome a host with a wide spectrum of resistance.

Jensen (1988) cites one example of success with this method: the Australian wheat variety ‘Timgalen’, which has remained field-resistant for 20 years, though rust strains capable of attacking its individual genes were present.

There are two different approaches to breeding for multigenic resistance: to incorporate different genes for resistance within the same genotype, or, alternatively, within different related genotypes, to constitute a composite cultivar (Hanson et al., 1979a). Such multiline cultivars are mixtures of lines, usually near-isogenic, which differ from each other in resistance to a specific race of pathogen. As new races emerge, the newly susceptible lines are withdrawn from the mixture and replaced by resistant lines, if and when available. The first multiline wheat cultivar was Miramor 63, made up of 10 lines of wheat selected from 600 lines, developed in Colombia for resistance to stem rust and stripe rust (Kommendahl and Windels, 1979).

Multiple disease resistance. The limitations in breeding for resistance to a single disease, whilst the new cultivars remain susceptible to other, possibly no less harmful diseases, have led to breeding for multiple disease resistance, in which the objective is to develop cultivars that are resistant to the major diseases affecting the crop. This objective is evidently even more difficult to achieve than resistance to a single disease; that it is possible has been demonstrated in a number of cases, such as barley cultivars with resistance to five diseases, a lucerne strain, also with resistance to five diseases, and bean cultivars with resistance to several races of rust and to bean mosaic virus (Hanson et al., 1979b).

Disease tolerance. The concept of plant resistance or immunity is being replaced by that of disease tolerance. A specific resistance to a given race of pathogen is more absolute than multigenic resistance to a broad spectrum of races, disease-tolerant plants are not immune to the disease, but can resist massive infection and produce a reasonable crop.

Integrated control

The efficacy of most fungicides is directly related to the amounts of inoculum present at the time of application. Above a certain threshold, fungicides are generally unable to provide adequate protection. Hence the need to use cultural methods to prevent the build-up of inoculum to levels the chemicals cannot control; and to use chemicals early enough to prevent build-up beyond the limits of varietal and age-related resistance (Palti, 1981).

As is the case for weed and insect control, the combined application of all methods of disease control available to the farmer is the only long-term acceptable approach to ensure sustainable and economic yields. The use of resistant varieties, sanitation, weed control, improved tillage practices, and balanced nutrition will prevent or attenuate disease attack or increase the ability of the plants to withstand the onslaught of pathogens.

Chemicals should be used when these means are no longer able to prevent the build-up of inoculum to levels with which the plant, unaided, can no longer cope, and when the probable crop losses will exceed the economic threshold level (cf. p. 856).

Disease monitoring could be valuable in aiding the farmer to decide when to intervene most effectively with chemical treatments. Disease monitoring, in contrast with insect monitoring, has not been utilized extensively. For some crops, disease monitoring is not based exclusively on pathogen monitoring, but can rely on the monitoring of environmental conditions, on the assumption that inoculum is always present, and that an epidemic will occur when conditions are favourable (Tschirley, 1979). For example, late blight of potato (*Phytophthora infestans*) requires rainy weather and temperatures lower than 22°C, and there is little probability of an outbreak when these conditions do not pertain.

Microcomputers have been developed which monitor weather conditions in the field and warn the farmer when conditions are favourable for the outbreak of a specific disease.

In the USA, the Department of Agriculture, in cooperation with the State Agricultural Experiment Stations and Extension Service, operates a plant disease forecasting and warning service, thereby contributing to a considerable reduction in the number of routine sprays, otherwise used as preventive measures.

Integrated control of peanut stem rot

An example of integrated control management is the control of the peanut stem rot, caused by *Sclerotium rolfsii*. The procedure followed comprises (Graham, 1979):

- crop rotation;
- ploughing-under plant residues after harvest in order to prevent the build-up of inoculum;

- flat cultivation between rows to control weeds, without throwing soil and debris around the plant base;
- control of leaf spot with fungicides to prevent accumulation of dropped leaves on which the fungus can grow;
- application of an antagonistic organism (*Trichoderma harzianum*) for biological control.

Overall, the efforts of individual farmers must be backed by communal efforts, government backing and services, and appropriate legislation.

Descriptive and predictive models

Tschirley (1979), in writing on predictive models by which management decisions can be made, as the ultimate objective of disease management, states that “the process entails the collection and integration of several sets of complex data, with each relating to a dynamic biological, physical, meteorological, or socio-economic subsystem. The process can be facilitated by systems analysis and mathematic modeling”. Therefore, the major obstacle to the development of models is the lack of basic biological data and its relation to climatic factors.

Notwithstanding the difficulties and complexities mentioned above, predictive models for a number of diseases (as well as for insects) have been developed and are being used (Tschirley, 1979).

Bacterial diseases

Although the number of bacterial diseases is small, relatively to fungal and viral diseases, bacteria attack all major crop plants and can cause considerable damage. Symptoms include leaf spots, wilting, blight, galls, and cankers (Graham, 1979). They penetrate plant tissues through the stomata, or through wounds, such as those caused by insect feeding or mechanical injury.

The bacteria do not form spores, but survive adverse conditions in their hosts; they produce short-lived vegetative cells that are propagated by wind, rain, and irrigation.

Control

The rapid entry of pathogenic bacteria into the plant tissues protects them from most chemicals applied to the foliage; they are also not highly susceptible to organic fungicides.

Control measures include: disease-free seed, produced in arid areas with low bacterial populations; disinfected seed (hot water treatment), sanitation, resistant varieties, cultural practices, the use of bacteriophages, the use of bacterial species indigenous to a host plant, to suppress virulent bacterial pathogens. Some bacterial diseases can be controlled by systemic antibiotics (Graham, 1979).

Plant viruses

Viruses can be defined as “transmissible, intracellular parasites that differ from other forms of life in having no intrinsic metabolism and only one type of nucleic acid, either DNA or RNA” (Siegel and Hari, 1980).

In essence, viruses are fragments of nucleic acid genetic material that depend on a host cell for their replication.

A virus particle consists of its nucleic acid enveloped by a protein, and occasionally also a lipid-containing membrane. After entry into the cell (see below) the genetic material must be released from its protein cover, the viral genetic material must be translated and replicated, and new virus particles formed by assembly of the viral genome and other constituents.

Some diseases formerly ascribed to viruses are caused by mycoplasmas, viroids, and Rickettsiae.

Methods of virus disease transmission

Most plant viruses have several methods of natural transmission (Walkey, 1985).

Plants do not become infected simply by being exposed to high concentrations of virus inoculum; the virus must gain entry into the cell. There has to be some mild type of wounding by direct contact or by the intermediary of vectors (Siegel and Hari, 1980). Transmission in the field by natural mechanical damage to plant tissues is relatively rare, and probably of minor economic importance; it occurs mainly with very stable viruses that multiply to very high concentrations in the plant (Walkey, 1985).

Direct contact occurs through mechanical wound sites, with transmission by Man and his tools, or by animals; also by contact of healthy plants rubbing against diseased plants; other forms of direct transmission are via infected seeds, planting material or pollen.

The most common sources of infection are: (a) the planting material – seeds and more frequently vegetative materials; and (b) crop residues, weed plants, neighbouring fields, and vectors.

Many viruses in diseased plants are not transmitted by the seeds; others are able to survive in endosperm, embryo, or seedcoat and infect the germinating plant. Though only 27% of the known plant viruses are seed-transmitted, seed infection plays a major role in the transmission and survival of a number of important virus diseases (Walkey, 1985).

The amount of infected seed in a commercial seed batch may be very low because it is diluted by seed produced from healthy plants, but even a small percentage of infected seeds can become a source of inoculum for an entire field. The secondary spread of the virus through the crop frequently occurs by aphid transmission. Seed transmission is also an ideal means for virus survival under unfavourable conditions.

Vegetative propagation of crops, through cuttings, tubers, runners, or bulbs from

diseased plants is a very efficient method to spread viruses, without the virus having to penetrate and establish infection in new plants. Therefore, in vegetatively propagated crops, virus-free planting stock is of major importance.

Stubble and roots from cereal crops, ratoons from cotton, volunteer plants from potatoes and sugar beets, etc., can transfer the inoculum from virus-infected plants to the next crop. Wintered plants can be the main source of beet mosaic and beet yellows virus infection in newly planted sugar beets in California (Palti, 1981).

Weeds are a source of virus infection for many crops, especially in the case of viruses and their vectors that have a wide range of hosts. Infected trees, shrubs and other plants growing around crops or in the field, may provide a reservoir of virus infection.

The control of weeds and other plants growing along headlands by cultivation, burning, or herbicides, is often an effective way of preventing the spread of viruses from these sources (Bos, 1981).

Transmission by vectors

The most common vectors are insects, mainly aphids and leafhoppers. Other vectors include arachnids, nematodes, and fungi. There are several types of virus-vector relationships:

(a) *Nonpersistent* or *stylet-borne* type in which the vector becomes a carrier after feeding for a few minutes on an infected plant, and remains infective for only a very short period. The ability to infect is also lost on moulting. The nonpersistent mode of transmission of viruses is the most common and causes considerable economic damage (Walkey, 1985).

(b) *Persistent* or *circulative* type in which the vector feeds for a somewhat longer time on the host plant; there is a latent period of hours to days before the virus can be transmitted to a healthy plant; the vector remains infective for days to weeks; and the virus carrier remains infective after moulting. The virus may multiply in the vector (propagative type) such as lettuce necrotic yellows, or does not multiply in the vector (circulative type), such as barley yellow dwarf virus (Walkey, 1985).

(c) The *semi-persistent* type is intermediate between the two former types, and can be considered as stylet-borne but persisting for a somewhat longer period, though usually not through a moult.

Helper viruses: Certain viruses, of all three types described above, can only be transmitted by aphids, if the source plant on which the vector feeds is infected by a second virus. For example, barley yellow dwarf (MAV strain) is transmitted by *Rhopalosiphum padi* if the source plant is also infected by barley yellow dwarf (RPV strain) (Walkey, 1985).

Aphid transmission

The most effective vectors are the aphids, which have a tremendous reproductive

capacity; some of these have a wide range of hosts. For example, *Myzus persicae* is an important vector for about 70 different viruses, and feeds on a large number of weeds and crop plants (Siegel and Hari, 1980).

Leafhopper transmission

The second most important vectors are leafhoppers. Viruses transmitted by these vectors generally cause yellowing and leaf-rolling in the infected plant, and only a few are sap-transmissible. The viruses are mostly concentrated in the phloem cells; most are transmitted in a persistent manner. Exceptionally, rice tungro and maize chlorotic virus behave like semi-permanent viruses, persisting only a few days in their vectors and having no latent period (Walkey, 1985).

The leafhopper vector of sugar beet curly-top virus (*Circulifer tenellus*) can be moved long distances from infection sources. The virus and its vector winter in warm areas of California, Texas, Arizona, and New Mexico, where large populations of leafhoppers are produced in winter and early spring. Winds then carry the leafhoppers for considerable distances to infect beet crops over wide areas (Duffus, 1973).

Whitefly transmission

Virus diseases transmitted by whiteflies are of considerable economic importance in tropical, subtropical and Mediterranean regions. They attack major food crops, such as cassava, bean, soybean, sweet potato, tomato as well as cotton; the major symptoms are mosaic and leaf distortion. The most important and widespread vector is *Bemisia tabaci* (Walkey, 1985).

Mites serve as vectors for a number of virus diseases; as they cannot fly, they spread the disease by crawling from one plant to the other or by wind dispersal. Because of their small size, even a light breeze can dislodge them and carry them away. Soil fungi and nematodes of the genera *Xiphinema*, *Longidorus* and *Trichodorus* are the vectors for soil-borne viruses.

Plant susceptibility

Many vectors are attracted to young, tender plants for feeding, and these are therefore more susceptible to infection than older plants. Similarly, well fertilized, vigorously growing plants are more prone to infection than smaller, less vigorous plants.

Control methods

Considerable progress has been made in the control of plant viruses; however, it has not yet been found possible to inactivate plant viruses during their replication, without inflicting considerable damage to the host plant (Siegel and Hari, 1980). Therefore, control measures are based on preventing infection or mitigating the consequences of infection.

The major control methods are:

Virus-free seed and planting material. The meristem of many vegetatively propagated crop plants is generally free of the disease and virus-free planting stock can be prepared through tissue culture. In some cases in which this method is not feasible, heat therapy can provide an answer. Dormant plant parts can be heated in water at temperatures that are just below lethality, or by growing plants at temperatures as hot as they can tolerate for a few weeks.

Propagation material from vector-free areas. Growing crops to be used as a source of propagating material in areas in which the vector is absent is very effective. The typical example is the growing of seed potatoes in relatively cool and windy regions in Scotland and Ireland, for planting in the virus-prone Mediterranean countries.

Legislation may regulate the distance between the certified seed-producing areas and the areas for commercial production in the countries specializing in the production of virus-free seed potatoes.

Roguing. The removal of diseased individual plants within the crop, when they are still young, when a few plants may be the foci of infection, is very effective.

Interrupting the infection cycle. This can be achieved by controlling planting and harvesting dates, so as to ensure a host-free period during the year; in the Sudan, for example, the effect of time of planting on the occurrence of broad bean mosaic virus, transmitted by an aphid, is considerable (Abu Salih et al., 1973). Another example is that of maize rough dwarf disease, transmitted by a planthopper, *Laodelphax striatella*, which assumed epidemic scale in maize sown traditionally in early spring. Research demonstrated that the virus cannot multiply in the vector after early June; by sowing late in May, the incidence of the virus was reduced from 45% to 3% (Harpaz, 1982). These methods require legislation or organized communal effort in order to be effective.

Sanitation. Control of weed hosts; destruction of infected crop residues and other common-sense measures to prevent spread of the disease by workers, implements, etc.

Crop barriers. A crop barrier, such as barley, for example, sown around a susceptible crop, may cause the aphids to land, probe briefly, and lose non-persistently transmitted infectivity.

Optical means for virus vector control. These consist of coloured materials that attract the vectors, reflectant surfaces that repel them, and netting that prevents their reaching susceptible plants (Palti, 1981). Aphids are attracted to yellow polyethylene sheets, placed vertically, on the windward side, along rows of the plants to be protected; the sheets are covered with a sticky substance that traps the aphids. The method

has been found to be moderately effective in reducing incidence of the cucumber mosaic virus (Cohen and Marco, 1973) and potato leaf roll virus in fields of seed potatoes (Zimmerman-Gries, 1979).

The yellow colour of straw mulches attracts whiteflies (*Bemisia tabaci*); this method has been used in Israel to protect cucumbers from cucumber vein yellowing virus and tomatoes from tomato yellow curl virus. Yellowish wood shavings may also fulfill the same role (Cohen, 1982).

The reflectant surface of aluminum strips, grey or white plastic sheets, used as mulches, was found to reduce the number of winged aphids by about 90%, and afforded protection to pepper plants from cucumber mosaic virus and potato virus Y in Israel (Loebenstein et al., 1975) and from water melon mosaic virus in California (Wyman et al., 1979).

White polyethylene nets, placed 0.5 m above pepper plots, reduced infection by the same two viruses. The nets not only repel aphids, they also obscure the host from the vectors (Palti, 1981).

Chemical control of insect vectors. *Systemic insecticides* are effective against vectors of persistent viruses; in the case of non-persistent viruses, the plant becomes infected within seconds after the insect starts feeding. The number of sprays needed can be significantly reduced by careful timing based on a warning system that forecasts virus spread when aphid numbers increase above a certain threshold (Walkey, 1985). Application at planting of systemic insecticides in the form of slow-release granules is more efficient than spraying for some viruses.

Oils, such as paraffin, mineral oil, or albolineum, sprayed on the foliage of susceptible plants, may prevent aphid transmission of non-persistently transmitted viruses (Loebenstein et al., 1970). Problems in using oil sprays include phytotoxicity and easy removal of the oil layer by rain or irrigation (Walkey, 1985).

Soil fumigation, if soil tests indicate the presence of virus-carrier fungi and nematodes (cf. p. 899).

Biological control. Harpaz (1982) found that the low incidence of barley yellow dwarf virus in Israel is due to the presence of natural enemies of the vector; a possible confirmation of this view is the successful control of this virus in Chile by the predator insect *Aphidius ervi* (Van den Bosch, 1976). On the whole, control of virus vectors by predators, parasites, or pathogens, has not been very successful (Walkey, 1985).

Cross-protection. Preinfecting certain host species with a mild virus pathogen makes it possible to protect the host from subsequent infection by a more destructive virus pathogen. For example, when tomato plants are inoculated with a mild strain of curly-top virus, they are resistant to most other, more virulent strains (Loebenstein, 1963).

Breeding for virus resistance

Natural resistances

Resistance to virus infection can be *passive*, such as mechanical barriers, and lack of metabolites required for virus multiplication, or *active*, i.e., defences that develop after infection. These may lead to structural changes that interfere with viral replication or translocation (Loebenstein and Stein, 1985).

The most notable active defence is *local lesion response*, whereby after inoculation, the virus invades and multiplies in several hundred cells, but does not spread to other tissues.

Achievements and limitations

Because chemicals that might affect the virus also harm the host plant, the breeding of resistant or tolerant plants is the most effective approach in virus disease control (Loebenstein and Gera, 1988). Considerable effort has been invested in breeding cultivars that are resistant to virus diseases. The basic principles are the same as those described in breeding for insect resistance (cf. p. 852) or fungal disease resistance (cf. p. 902) according to whether the target is the vector or the virus. Virus-resistant cultivars are of particular importance for controlling viruses that are transmitted by aphid vectors in a non-persistent manner, because the vectors of these viruses are not controlled by insecticides.

Notable achievements in breeding virus resistant cultivars have been made, such as cucumber cultivars resistant to cucumber mosaic virus (CMV).

Traditional breeding procedures are limited by the relatively few sources of resistance available in related species in which genetic transmission is possible. In order to overcome this constraint, the use of DNA technology, to manipulate and transmit resistance sources, has been advocated (Chet, 1987). Little practical work on this approach has yet been activated. Current approaches consist in inserting viral genes, and antigene strategies to obtain resistant plants (Loebenstein and Gera, 1991).

Mycoplasma diseases

Many diseases characterized by stunting, chlorosis, yellowing of leaves, changes of flowers into leaf-like structures, etc., formerly thought to be virus diseases, are now known to be caused by mycoplasmas (Kranz et al., 1977).

Mycoplasmas are smaller organisms than bacteria; they are bigger than viruses, but filtrable like them. They have no cell walls. Mycoplasmas reproduce by budding, fission or forming chains. They are transmitted from plant to plant by leafhoppers, planthoppers, and psyllids as vectors.

Control measures are similar to those for virus diseases, including heat therapy. Valuable plants can be treated by injecting antibiotics, such as tetracyclines (Kranz et al., 1977).

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